A SYSTEM MODEL FOR ASSESSING WATER CONSUMPTION ACROSS TRANSPORTATION MODES IN URBAN MOBILITY NETWORKS

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A SYSTEM MODEL FOR ASSESSING WATER CONSUMPTION ACROSS TRANSPORTATION MODES IN URBAN MOBILITY NETWORKS

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LIST OF ABBREVIATIONS

HOV	High-Occupancy Vehicle
GHG	Greenhouse Gas
EIOLCA	The Economic Input-Output Life Cycle Analysis Model
VMT (VKT)	Vehicle-Miles Traveled (Vehicle-Kilometers Traveled)
DVMT (DVKT)	Daily Vehicle-Miles Traveled (Daily Vehicle-Kilometers Traveled)
WTW	Well-To-Wheel
WTT	Well-To-Tank
WTP	Well-To-Pump (Used along with TTW)
TTW	Tank-To-Wheel
PTW	Pump-To-Wheel (Used along with TTW)
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
PV	Photovoltaic Solar Power
LCA	Life-Cycle Assessment
HOV	High-Occupancy Vehicle
EOR	Enhanced Oil Recovery
PADD	Petroleum Administration for Defense District
VOC	Volatile Organic Compound
CO_2	Carbon Dioxide
EPA	Environmental Protection Agency
PHEV	Plug-In Hybrid Electric Vehicle
HEV	Hybrid Electric Vehicle
BEV/EV	Battery-Powered Electric Vehicle

LDV	Light-Duty Vehicle
NGV	Natural Gas Vehicle
PVMT	Passenger Vehicle-Miles Traveled
MIPS	Material Inputs Per Service Unit
ISO	International Organization for Standardization
MBSE	Model-Based Systems Engineering
SysML	Systems Modeling Language
INCOSE	International Council on Systems Engineering
OOSEM	Object-Oriented Systems Engineering Method
RUP	Rational Unified Process
MAsCOM	Multi-Aspect Component Model
UML	Unified Modeling Language
EAM	Engineering Analysis Model
WTW	Well-To-Wheel
MATLAB	The MathWorks Matrix Laboratory Numerical Computing Environment
IC (ICE)	Internal Combustion (Internal Combustion Engine)
CNG	Compressed Natural Gas
LPG	Liquefied Petroleum Gas
LNG	Liquefied Natural Gas
OECD	Organization of Economic Co-operation and Development
TTI	Travel Time Index
IGCC	Integrated Gasification Combined Cycle
NGCC	Natural Gas Combined Cycle
eGRID	Emissions & Generation Resource Integrated Database
EIA	Energy Information Administration

LIST OF SYMBOLS

$W_{WTW\text{-}Use}$	Well-To-Wheel Use-Phase Water Consumption Rate
$V_{usePhase}$	Total Daily Use-Phase Water Consumption Volume (Per Vehicle)
$V_{fleetServicing}$	Total Daily Use-Phase Water Consumption Volume (Per Fleet)
$n_{vehicleMode}$	Vehicle Market Share Percentage
X_{fleet}	Total Number Of Vehicles (Per Fleet)
W_{fuel}	Fuel Consumption-Based Water Consumption Rate
W_{fluid}	Vehicle Auxiliary Fluid Usage-Based Water Consumption Rate
d_{daily}	Daily Vehicle-Kilometers Traveled
$V_{fleetServicing}$	Total Daily Servicing Water Consumption Volume (Per Fleet of Autos or Buses)
$V_{service}$	Daily Servicing Water Consumption Volume (Per Vehicle)
$V_{washing}$	Daily Washing Water Consumption Volume (Per Vehicle)
W_{road}	Road Infrastructure Use-Phase Water Consumption Rate
$W_{roadMaterial}$	Road Material Consumption-Based Water Consumption Rate
$W_{roadElectricity}$	Road Electricity Consumption-Based Water Consumption Rate
$W_{roadEquipmentFuel}$	Road Heavy Equipment Fuel Consumption-Based Water Consumption Rate
$V_{roadNetwork}$	Total Daily Road Network Use-Phase Water Consumption Volume
$d_{collector}$	Total Road Lane Distance For Collector Roads
$d_{arterials}$	Total Road Lane Distance For Arterial Roads
$d_{arterials}$	Total Road Lane Distance For Highways
V_{total}	Total Daily Network Use-Phase Water Consumption Volume
η_{EV}	Aggregate Electric Vehicle Component Efficiency

η_{charge}	Electric Vehicle Battery Charge Efficiency
$\eta_{discharge}$	Electric Vehicle Battery Discharge Efficiency
η_{motor}	Electric Vehicle Motor Efficiency
η_{shaft}	Electric Vehicle Drivetrain Efficiency
FE	IC Vehicle Fuel Efficiency
EE	Electric Vehicle Energy Efficiency
W_{WTP}	Total Well-To-Pump Fuel Production Water Consumption Rate
$W_{extraction}$	Fuel Extraction Water Consumption Rate
$W_{process}$	Fuel Processing/Refinement Water Consumption Rate
$W_{transport}$	Fuel Transport/Distribution Water Consumption Rate
$W_{infrastructure}$	Fuel Infrastructure Construction Water Consumption Rate
$W_{compression}$	Fuel Compression (CNG) Water Consumption Rate
$\eta_{gasCompressor}$	Natual Gas Compressor Efficiency
$r_{compression}$	CNG Gas Compression Ratio
$e_{compression}$	CNG Electric Compressor Electricity-Gas Ratio
$W_{WTP-electricity}$	Electricity Generation Mix Water Consumption Average
W_{source}	Total Electricity Generation Source Water Consumption Rate
W_{plant}	Power Plant Water Consumption Rate
E_{source}	Total Electricity Generation Source Energy Output
E_{total}	Total Electricity Grid Energy Output
$\eta_{transmission}$	Electricity Transmission Grid Efficiency
V_{fuel}	Vehicle Fuel Consumption Volume
$m_{material}$	Material Flow Mass
$E_{consumed}$	Infrastructure Energy Consumption Rate

SUMMARY

Energy and environmental impacts are two factors that will influence the composition of urban transportation networks in the near future. One such emerging issue is the effect of water consumption resulting from changes in regional or urban transportation trends such as in utilizing alternative energy sources and consolidating urban regions. With numerous localities experiencing stresses on water availability, key stakeholders - planners, manufacturers, and vehicle end-users - need to combine information on transportation-related water consumption for any urban region and assess any potential impacts on local water resources from the expansion of alternative transportation modes. This thesis will focus on the investigation of use-phase water consumption factors within urban transportation networks for private automobile and public bus fleets, as well as on alternative fuels that may emerge as key elements in future mobility networks - biodiesel, ethanol, compressed natural gas, and electricity for battery-electric and plug-in hybrid vehicles - along with energy and fuel production pathways as well as for road and vehicle operation infrastructure for a given network.

While there are several studies that examine life cycle water impacts for certain fuels, vehicle types, and electricity generation, few repeatable models exist in terms of assessing overall water consumption across several transportation modes within urban or regional areas. Based on these premises, the question is as follows: is it possible to develop a reusable and traceable decision support tool that combines water consumption from all possible transportation modes and related mobility infrastructure for a given transportation network, from which such consumption can be evaluated with respect to

local water resources and transportation-related policies? To help address this question, a reusable, object-oriented system model combining a structural and parametric breakdown of transportation system elements was developed using the Systems Modeling Language (SysML) and Model-Based Systems Engineering principles in order to provide a comparison of water consumption across conventional and alternative vehicle technologies for assessing the resiliency of existing mobility infrastructure and network-wide water resources.

To demonstrate the intent of this model, daily transportation network water consumption will be analyzed for current and alternative transportation network scenarios projected by policies regarding the expansion of alternative fuels within the near future. Based on this case study and associated scenarios, the model is expected to show variations in water consumption due to regional fluctuations in energy pathways, vehicle market shares, and driving conditions, from which the model should help determine how much potential impact each alternative transportation mode may have on each location and whether or not it is feasible to expand the operation of said modes in these networks. Although spatially explicit data is comparatively limited to the current and projected national and regional averages that are used as model and case study inputs, the analytical framework within this model closely follows that of existing assessments and the object-oriented, reusable nature of SysML model elements allows for the future expansion of additional transportation modes and infrastructure as well as other environmental impact analyses.

CHAPTER 1

INTRODUCTION AND BACKGROUND

1.1. Motivation: Water Scarcity

1.1.1. Water Scarcity in Urban Regions

As an essential natural resource, fresh water is a prerequisite for all life on Earth. Specifically, humans are inextricably linked to water for a range of applications from drinking water and hygiene to water for manufacturing the goods that are essential to daily life or for irrigating crops that provide much-needed food resources. With water as such an indispensible resource, humans have consequently developed communities around utilizing water resources for agriculture, industry, and sustenance.

However, as urban regions grow and populations expand across the world, water resources management has become an increasingly important issue as many of these communities are expanding in water-stressed areas and subsequently are extracting water from more remote sources (United Nations, 2009). This is exacerbated by increased water consumption resulting from the consumption of more manufactured goods, livestock, agricultural products, and energy sources. With current projections showing that 86 percent of the population in more developed countries and 68% in less developed regions will live in urban communities by 2050, there is a heightened risk that many of these regions will experience water scarcity and engage in disputes with other regions over dwindling resources for commercial, residential, or industrial uses (United Nations, 2007; Gleick, 1993). Notable examples of existing or emerging conflicts over water resources include the decades-long fight between Georgia, Alabama, and Florida for access to water from the Chattahoochee River Basin, disputes between Los Angeles and Owens Valley over water availability, as well as numerous armed conflicts in India, the Middle East, and in other water-stressed regions around the world (Atlanta Regional Commission, 2010; Morrison et al, 2009).

Even in more developed regions such as that of the United States, many localities are experiencing increased demands for underground or surface freshwater resources, especially as populations or industry expand. Currently, the vast majority of freshwater consumption in the United States is attributed to power generation, irrigation for agriculture or energy crops, and domestic (public supply) use; as urban populations expand, there will subsequently be increased competition between these two sources of demand and other components such as commercial, industrial, or transportation water use (Kenny, et al, 2009; **Figure 1**). Another factor to consider in addition to increased populations and corresponding water demands is the effect of climate change on water resources. The use of fossil fuels and subsequent increase in greenhouse gases have been linked to higher temperatures, increased rainfall, and ultimately shifts in climate in numerous areas around the world, resulting in more uneven water distributions ranging from flooding in some areas to severe water stress or drought in others. While a sizable amount of any runoff from increased precipitation and flooding is available as clean drinking or potable water, any increase in available runoff cannot keep up with projected population increases in the foreseeable future (Postel, 2000).

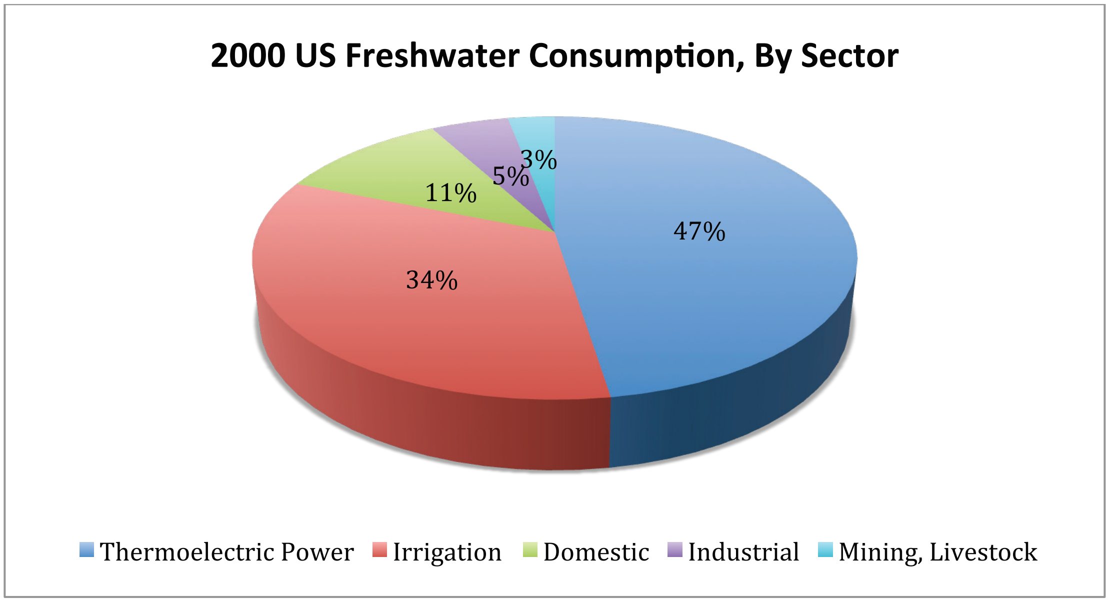


Figure 1. U.S. Freshwater Consumption, 2000, By Sector (Hutson et al, 2005).

Based on these factors, it is no surprise that water scarcity and the issue of competing water demands has become a global issue on par with the issue of greenhouse gases and global warming (Gleick, 1993). With the onset of climate change and increased population consumption patterns, the issue of water scarcity will affect all aspects of urban regions as limited or abused water resources will stem economic growth, pose public health problems in terms of declining water quality and quantity for sanitation and domestic use, and exacerbate food shortages across the world. As such, action is needed in order to stabilize water usage and manage water resources effectively in order to ensure resiliency in the economic and social development in urban regions around the world.

1.1.2. Interdependence Between Water and Energy

Water and energy are inherently intertwined and are two primary factors for economic and population growth (Carrillo and Frei, 2009). This is rooted in the fact that supplying energy requires water in all aspects of electricity or energy generation and distribution (Merson et al, 2006). Many of the fuels required for producing energy require large quantities of water for extraction or mining and are potentially from regions with limited water resources, and such water is either in constant competition with water demands for those areas or severely polluted from these processes. Similarly, large amounts of water are required for processing, refining, or distributing these fuels, whether it be in terms of water for refining petroleum or water used to transport coal slurry through vast pipelines (Gleick, 1993). Even more water is required for burning these fuels through thermoelectric power generation as these power plants consume and withdraw significant amounts of water for cooling, maintenance, or other functions essential for their operation (Merson et al, 2006; Feeley et al, 2008).

Based on these interdependencies, it is important to balance water demands and availability together with growing energy demands, especially in regions where water availability is a premium. Given that electricity generation represents such a significant amount of water withdrawals in the United States overall, and given that the advent of biofuels and bioenergy would also encroach on irrigation-related water usage, it is vital to ensure that increases in energy consumption do not hinder water resources for other economic sectors and potentially cause water conflicts between competing groups within an urban region.

1.1.3. The Importance of Water In Urban Transportation

Urban regions today constantly need to decide on the allocation of water resources to irrigation, industrial, commercial, domestic, and other uses required for sustaining economic development and public health or well being. One additional component previously overlooked in examining water demands is the transportation network or system for a given region. As with energy production, transportation and water are just as intertwined.

Just as water is essential for all aspects of electricity production, water is a primary component in producing the fuels necessary for powering the transportation modes needed to sustain an urban region. Many urban areas in the United States and the developed world have developed infrastructures based on the prevalence of automobiles or rail transport. Water is extensively used and consumed in extracting and refining petroleum for gasoline or diesel for passenger, commercial, or public transit vehicles; even more water is required for manufacturing and operating these vehicles. Similarly, water is needed in all aspects of any supporting urban transportation structure. For example, water is required in producing the concrete or asphalt for constructing or maintaining roads, de-icing or resurfacing of these roads and highways, as well as any associated electricity for maintaining any associated lighting or sensors (Spielmann et al, 2007). Similarly, water is needed for the construction, maintenance, and electric power delivery for municipal rail systems.

Any significant urban population growth and corresponding increases in vehicles will ultimately overwhelm existing transportation infrastructures, as the excess vehicle amount will cause bottlenecks and additional traffic congestion with existing road systems, resulting in wasted fuel, increased delays, and rising costs; for example, total congestion costs in the United States for 2007 have increased fivefold since the 1980s due to 2.8 billion gallons of wasted fuel and 4.2 billion hours in delays (Schrank and Lomax, 2009). While congestion-mitigating measures such as increases in carpool or HOV lanes or increased public transportation implementation and usage, these measures require water to some degree rather in the construction and additional maintenance of high-capacity traffic corridors. These developments should definitely account for projected transportation trends in any urban region, but they must also be examined in terms of water impacts and usage so as that such urban transportation development does not provide excessive strain on local water resources.

1.1.4. The Emergence of Alternative Fuels and Associated Impacts on Water

Recent concerns regarding the greenhouse gas (GHG) emissions from petroleum-based transportation fuels such as gasoline and diesel have motivated regional, national, and global stakeholders to consider alternative, renewable fuels for energy and transportation systems. Furthermore, a significant amount of fossil fuel is imported into the United States from foreign sources such as the Middle East or South America, and many more reserves are in geographically or politically challenging locations (Harto et al, 2010). Proponents of alternative fuels have noted that many biofuels such as biodiesel or ethanol can be produced from readily-available energy crops grown locally or domestically, noting that the implementation and expansion of these fuels would increase energy security as these would decrease overall dependence on fossil fuels from domestic or foreign sources (Gerbens-Leenes et al, 2008). As such, biomass and biofuels have recently been identified as key elements to numerous potential sustainability frameworks due to its supposedly carbon-neutral production and consumption and potential to diversify energy resources and increase the resilience and sustainability of transportation and power generation for any given region.

Another alternative transportation mode, albeit a more longstanding technology compared to the recent rise in biofuel technologies, currently under consideration is the battery electric propulsion system for automobiles and buses. While the electric motor and battery have been around for at least a century and have been implemented in some of the earliest automobiles, electric vehicles have only recently become another potentially sustainable transportation mode as many policies and studies have focused on transitioning current transportation systems to electric-driven ones (King and Webber (1), 2008). Proponents of battery-electric vehicles note that EVs offer significant environmental improvements over current vehicle types by limiting or having no local greenhouse gas emissions, especially in areas with renewable energy sources, and lessen our overall dependence on petroleum as a transportation fuel (Delucchi et al, 2001).

Numerous battery-electric technologies have been implemented into prototypes or production vehicles, such as lithium-ion battery systems installed in the recently-released Nissan Leaf and the Tesla Roadster, plug-in hybrids that can run off the electric grid or with a gasoline-fueled generator, or fuel-cell vehicles that use fuels such as hydrogen for electrolysis and energy generation. While common obstacles have been range anxiety due to the limited power output and battery life of early electric vehicles as well as a lack of infrastructure, there has been a recent push to integrate electric vehicle infrastructures into urban transportation networks. Many municipal utilities and agencies have already implemented some form of charging infrastructure and begun using a small number of electric vehicle prototypes in their fleets, and some municipalities, such as Vancouver, have already begun mandating charging hubs in residential areas in a preparation for wider acceptance of electric vehicles. Similarly, regional and national governments and industry stakeholders have implemented policies that support the growth of electric vehicles, with the EV20 Alliance of battery electric vehicle manufacturers setting a target of 1 million EVs on the road in the United States by 2015 and the Canadian government targeting 500,000 electric vehicles by 2018 through the use of EV-friendly infrastructural regulations, manufacturer incentives for electric vehicle development, and end-consumer tax credits (Elwood et al, 2010; The Climate Group, 2010).

While numerous studies and policies have focused on the benefits of implementing alternative fuel modes and infrastructures based on reduced emissions and increased energy independence, security, and resilience, little mention – until recently – has been made on any water-related impacts bioenergy and battery-electric applications may have on local resources. It is implied that the energy sources for both types of alternative fuels would be produced within a mobility network or its surrounding region, either in the form of corn, algae, or soy energy crops from the agricultural sector or the regional utility-derived electricity that is shared with domestic, commercial, and industrial electricity consumption in any region. Implementing multiple vehicles using these alternative fuels will undoubtedly increase demand for either of these two sources, as both components serve multiple uses of supplying either food or electricity needed for the current network.

Once we consider that these transportation modes can potentially induces stresses in either source's supplies, we need to consider any associated water costs for each fuel type. Several reports and studies have attempted to quantify water consumption for the production of each energy source, and all of them have come to the conclusion that the implementation of biofuels or electric vehicles will significantly increase water demands in the near future. For example, some researchers have noted that bioenergy presents a security risk for local agricultural production as any increased allocation of energy crops can significantly affect local or regional food supplies and prices (Gerbens-Leenes et al, 2008). This is coupled with the fact that agricultural water consumption constitutes approximately 80 percent of total water consumption in the United States and is likely to increase in response to increases in food demands and urban populations (Hutson et al, 2005; Wu et al, 2009). Based on such projections, an increase in bioenergy production will put additional stress on local water resources and land use (Gerbens-Leenes et al, 2008). That said, the major water consumption factor in bioenergy is irrigation required for producing the base energy crops needed for biofuel production, and there are significant regional differences in crop production as some base crops may need less induced irrigation (or none at all) in some regions than those in other areas of the United States or the world (Wu et al, 2009; King and Webber, 2008 (2)).

While electric vehicles are touted as a more environmentally friendly alternative to conventionally fueled vehicles in terms of emissions and direct fossil fuel consumption, it is important to note that any electric vehicle is as clean or sustainable as the electricity produced. Currently, the majority of electricity production is dominated by fossil or thermoelectric fuels, with coal and petroleum being particularly water-intensive in terms of processing, distribution and extraction, and numerous studies have reported that electric vehicles, in pump-to-wheel energy consumption, consume significantly more water during their operation compared to vehicles using conventional gasoline or diesel. That said, since the operational water consumption for electric vehicles is tied primarily to the makeup of the fuels needed for electricity generation, the water consumption (and indirect emissions) for electric vehicle operation can be reduced significantly by using renewable energy sources such as photovoltaic cells, hydroelectric power, or wind power, although some of these sources are not easily implementable in regions with limited surface water availability, sunlight, or wind conditions (King and Webber, 2008 (2)).

Not every alternative fuel is ideally suited for every single urban region in the United States, considering that every urban mobility network has different characteristics in terms of infrastructure, energy usage, travel time, mode preference, or congestion. Since these fuels or energy sources for transportation will serve as a cornerstone for sustainable and resilient transportation objectives and policies in the foreseeable future, it is more essential now to consider the implications in expanding those modes into any region. As there is more to the picture than what bioenergy and electricity-derived transportation modes present in terms reducing emissions and creating more sustainable and resilient fuel options, we simply cannot assume that transplanting or replacing an entire network with these alternative sources will lessen any environmental impacts to a given region. A suitable balance of each alternative and conventional transportation fuel is needed for any given network in order to ensure that local water resources remain sustainable and resilient for any regional growth.

1.2. The Need To Manage Water Resources in Urban Regions

The need for freshwater in some locations has led to water allotments, shifts towards full-cost water pricing, more stringent water quality regulations, growing community opposition, and increased public scrutiny over water practices. Given increased demands for finite freshwater resources, it is even more imperative for regional, national, and global stakeholders – developers, policymakers, local or regional officials, and relevant industries – to find ways to document and manage these resources. Models and assessments of the water footprints must be developed for better water management and to create more effective policies that help integrate water strategies into the national planning process and water concerns into all government policies and priorities, as well as to consider the water resource implications of these actions.

As such, global organizations and regional stakeholders have begun examining measures or policies that can help in managing increasingly scarce water resources effectively in countries or urban regions. Some advocate increasing the productivity of existing water resources (and thus decreasing water intensity) for domestic, industrial, or agricultural use; others have called for and analyzed the idea of water sharing between or within regions where multiple states or groups share common surface or groundwater reservoirs (Postel, 2000; United Nations, 2009).

The underlying prerequisite for such approaches to optimizing water use, however, is to determine how much water is used for particular economic sectors or products such as for energy generation, crop production, or manufactured goods, as many of these factors constantly compete with each other in localities and regions across the globe. Much of the research done by stakeholders, particularly those of corporate and governmental entities, have focused on the idea of a "water footprint" for a specific product or sector of which the water footprint is the total volume of water used for the entire supply chain of a product, service, or entity (Hoekstra and Chapagain, 2009). Based on this concept, research has been done on allocating water consumption for certain agriculture crops, consumer goods such as beverages as well as for overall nations and cities in terms of consumption patterns (SABMiller, 2008; Hoekstra and Chapagain, 2007; Jenerette et al, 2006). Additional research efforts have focused on life cycle assessments for water consumption or withdrawal transportation fuels and energy generation, and other life cycle assessments have focused on water consumption related to transportation usage for numerous modes and fuels. In terms of transportation systems, several studies and assessments have allocated water consumption factors for various road systems in Europe as well as direct comparisons to vehicle usage (Spielmann et al, 2007; Saari et al, 2007).

However, difficulties arise when examining water use impacts for specific urban regions, particularly in terms of road and rail transportation. While there has been extensive research on water impacts from producing certain goods and services such as for agricultural products or transportation, these studies focus mainly on national areas or for generalized circumstances. In other words, not much research has been done for allocating these water factors in the context of any specific urban region. Specifically, certain localities rely on one set of fuels for energy generation and transportation, while others may have differing water usage characteristics. Or, some localities may be more dependent on passenger vehicles and thus have more road infrastructure. Current assessment models, such as GREET, may allow for a localized boundary in terms of regional characteristics for various transportation modes but do not account for water impacts; other models such as Carnegie Mellon University's EIOLCA may have some insight on water-related impacts to specific economic sectors but do not provide much in the way of specific regional parameters or transportation characteristics, requiring additional studies to examine water consumption factors for vehicle usage. More importantly, with a vast amount of information on water consumption factors in agricultural, energy, domestic, or transportation sectors, how can we integrate these water usage factors to specific regions or networks? Furthermore, what metrics should be used in order to assess projected future water impacts on urban networks with respect to current water resources and transportation infrastructure parameters? One way to combine and assess region-specific water components (particularly for transportation) is through the framework of a sustainable and resilient urban mobility network, which will be described in the next section.

1.3. Motivation: Resilient and Sustainable Mobility Networks

Water scarcity and increased demands on local water resources is only one of many key factors directing the future development of urban regions, with other key parameters being congestion, social equity, energy, and the environment. Given the previously discussed factors of climate change, population growth, and limited water resources, it has become more imperative to develop infrastructures for urban regions that are resilient and sustainable (SINEWS, 2009). Much of the background on sustainable infrastructures can be traced to the Brundtland Commission Report presented to the United Nations General Assembly, which points out that current practices (in 1987) in maintaining human and economic progress drew excessive resources from stressed environments and presents the idea of sustainable development as a way for humanity to ensure that it can meet present needs without encroaching on the needs of future generations (Brundtland, 1987). The European Commission augmented this definition in terms of urban mobility by defining a "sustainable transportation system" as a system that "allows the basic access and development needs of individuals, companies and society to be met safely and in a manner consistent with human and ecosystem health, and promotes equity within and between successive generations" by limiting emissions, reducing waste, and maximizing renewable resources while minimizing non-renewable sources

(European Commission, 2003). This augmentation is placed into the context of transportation networks that consist of multiple infrastructure elements such as roads and electricity distribution elements.

Other definitions of sustainable transportation exist, but all of them focus on developing transportation solutions that are more efficient, less impacting on the surrounding environment, and more accessible to urban populations. The MIT Department of Urban Studies, for example, notes that there are three "mutually reinforcing" elements – environmental stewardship, social equity, and economic efficiency – that are central to urban sustainability (Doust and Black, 2009). Some definitions and visions of sustainable mobility focus primarily on revising land use patterns in order to centralize mobility around local communities by locating key services around or near residential neighborhoods, while other groups have focused mainly on increasing the efficiency or usage of certain transportation modes. Perhaps the most relevant definition for viewing water impacts through a transportation perspective stems from the Transportation Research Board, which emphasizes analyzing transportation systems instead of analyzing potential threats to those systems such as on how "environmental, economic, and social systems interact to their mutual advantage or disadvantage at various space-based scales of operation" (Litman and Burwell, 2006).

Another element of transportation networks under consideration is the resiliency of physical and infrastructural elements in these networks against unexpected changes in the surrounding environment. Resiliency and sustainability are inherently lined as resilient design is characterized by "enhancing the flexibility and adaptability" of transportation systems against internal and external risks such as abrupt changes in resource supplies or demands (SINEWS, 2009). In other words, resilience focuses more on the adaptability of any given network instead of simply maintaining current conditions or resource amounts for the foreseeable future (Milman and Short, 2008). While sustainable mobility accounts for a surrounding environment that is not at risk, mobility networks also need to account for instances where there may be sudden cuts in fossil fuels or electricity due to strikes, terrorist attacks, or excessive demand (Bragdon, 2009).

Based on these general definitions, various studies and projects have focused on developing frameworks for assessing water, energy, and transportation infrastructures with respect to their immediate environments. One such project undertaken by the University of Michigan's Sustainable Mobility and Accessibility Research and Transformation (SMART) program is the development of a "mobility hub network" that integrates multiple transportation modes and options coupled with information networks within a network that supports numerous hubs that facilitate multiple transportation modes such as municipal buses, light rail, or air transport. Such mobility hub networks have been implemented in cooperation with regional and corporate sponsors in several urban regions such as Chennai, India, where dedicated public transportation services are being combined with feeder services and mobility hubs in order to allow for passengers to make seamless transfers between public transportation and other modes (Cherubal, 2009; Bras, 2009). Other systems exist, such as the Intelligent Transportation Systems (ITS) being implemented in several urban regions; these systems implement a series of management systems ranging from traffic control to road maintenance as well as for public transit tracking or other statistics for multi-modal transportation systems (U.S. Department of Transportation, 2009). While not all concepts have been fully implemented into existing cities and regions, the ultimate goal for all of these concepts and projects is to minimize traffic congestion and streamline the movement of social and physical elements (people and vehicles) with management and tracking technologies.

Just as there are differing views on sustainable transportation and mobility, there are numerous metrics that have been defined or developed for measuring the performance and efficiency of these mobility networks. For example, many metrics are applied to traffic, mobility, and accessibility perspectives in a network (Litman, 2003). Some common metrics include measuring the travel time from certain points in the network to others as well as overall energy consumption in said network. Network traffic and congestion has also been used as a metric for assessing the sustainability of mobility environments as government agencies have readily available data on vehicle numbers for a given region as well as traffic statistics for key mobility and traffic corridors. The Urban Mobility Report, for example, has used travel times and delays for individual travelers and modes for numerous urban regions in the United States and compiled them into travel time indexes for each locality (Schrank and Lomax, 2009). Many studies and assessments focusing on mobility performance in comparison to resource usage apply metrics pertaining to travel distance for a specific unit, such as in person-miles for passenger or public transit vehicles or vehicle miles traveled (VMT) for a specific transportation mode, along with other vehicle and network-based metrics such as travel speed and fuel or resource efficiency (Litman, 2003; King and Webber, 2008 (1); Harto et al, 2010). In terms of accessibility, current metrics include those focusing on economic efficiency – monetary costs stemming from the implementation of mobility infrastructure, for example – and social equity – the distribution of network elements such as hubs or fuel stations in a given network, the number of connections (roads, paths, or other connectors) in a given region, the distribution of transportation nodes, and so on (Litman, 2003; Doust and Black, 2009). Other network indicators focus on land use impacts, air or water pollution, resource efficiency, and citizen involvement (Litman and Burwell, 2006).

With this sheer number of performance indicators of sustainable and resilient mobility networks, there are also some associated issues and discrepancies. Many of these studies' findings indicate that sustainable mobility has not been fully or efficiently implemented, with the main reason being that current sustainability objectives are being implemented individually by separate groups through reductive decision-making; without a unifying policy or framework, many of these narrow solutions will eventually clash with each other and produce more problems for developing resilient and sustainable mobility networks (Litman and Burwell, 2006). Furthermore, some of these metrics, such as travel time indexes or congestion factors, have been criticized for comparing congested conditions with unrealistic, free-flowing conditions and for not accounting for clustered urban growth versus sprawled regions (Cortright, 2010). Additionally, Litman and Burwell (2006) note that some sustainability objectives may actually lead to price imbalances and shift resource-intensive producers to other regions, and that overall objectives pertaining to reductions in certain transportation modes (such as automobiles) with the intention to reduce congestion and increase accessibility may disrupt social equity by depriving certain consumers of their preferred mobility modes (Litman and Burwell, 2006). Lastly, while some studies have examined transplanting alternative transportation modes in place of existing ones in a push to adopt alternative vehicles, these assessments would not be representative of actual regional conditions without any defined policies for expanding alternative modes (Delucchi, 2004).

More importantly, there is always the possibility that not all resilient or sustainable mobility objectives may apply to all urban regions or mobility networks. In other words, many sustainability objectives or indicators are not always spatially explicit (that is, applicable to a particular scope) and leave out other socioeconomic and geographical factors such as regional climate or resource availability (Milman and Short, 2008). Additionally, not every mobility measure can necessarily be available – while traffic information for a given network may be readily available, some factors such as congestion-related costs may not. As the focus is to assess water impacts from sustainable mobility elements in any network, it is important to apply measurable, traceable, and spatially explicit indicators within an objective assessment framework that also accounts for surrounding characteristics in terms of energy usage, accessibility, mode feasibility, and network-specific policies or plans.

CHAPTER 2

RESEARCH QUESTIONS

2.1. Initial Research Questions

The previous chapter's discussion on the issue of water scarcity, sustainable and resilient transportation, and the water impacts from every aspect of a transportation system provide some initial answers to the initial research question as described below. While several studies have focused already on water impacts for products and services, they focus solely on individual components such as for conventional or alternative fuels or for individual electricity sources, and few studies place these water consumption factors in the context of operating or maintaining transportation systems, particularly in a well-to-wheel perspective. This poses the first general question:

What is the total well-to-wheel water consumption of any given transportation mode?

As mentioned before, this question can be partially answered based on transportation mode specifications and statistics as well as on the studies that focus on individual inputs, as there are numerous life cycle assessments on water consumption in the production of petroleum gasoline and other fossil fuels as well as on biomass-based alternative fuels such as for ethanol and biodiesel. In terms of transportation modes, most of the studies that have focused on water consumption stemming from pump-to-wheel fuel consumption focus only on parameters that relate to direct vehicle operation such as fuel efficiency and driving range. That said, there are many other factors to consider for any transportation mode. Every mode, be it passenger vehicle, bus, or light rail, needs to be maintained in some way over a defined time period, in which water consumption can be traced to water inputted directly into servicing or from the generated electricity needed to run the facilities or equipment required to service these modes (Spielmann et al, 2007). Furthermore, as published fuel efficiency values for passenger vehicles or buses are calculated based on standardized driving cycles and conditions, these values may not accurately represent every transportation network or mode as fuel efficiency is highly dependent on traffic conditions, driving manners, or the vehicle's physical dimensions (Environmental Protection Agency, 2010). In other words, the overall water consumption factor for a given transportation mode is closely intertwined with its surrounding environment, particularly in the infrastructure required for maintenance and normal operation. This leads to the second question:

What are the water consumption factors relevant to a transportation mode's supporting infrastructure?

Many assessments have been made in terms of a vehicle's direct operation, but there is comparatively little research or assessment in terms of water consumption or inputs in the infrastructure or support elements for a given network. These components include the roads needed for passenger vehicles, buses, or trucks, fueling stations, service stations, car washes, and so on. Each component would most likely withdraw and consume water from local resources as many supporting infrastructure elements are tied to commercial or industrial water consumption.

2.2. Core Research Question

The above initial research questions help to focus on water impacts for any given transportation mode and its surrounding infrastructure, but for a more complete understanding of transportation-related water consumption within an urban mobility network, a more comprehensive assessment of water consumption is needed. While the mobility network concept has been the subject of focus on environmental emissions and future transportation planning, there has been relatively little focus in considering aggregate water consumption based on a transportation network's activities. Urban mobility networks consist of numerous scales and levels of transportation elements – from the entire road network to the regular maintenance of a single vehicle – that need to be considered for a more comprehensive outlook on regional water impacts from transportation, even as many lifecycle and sustainability analyses focus in depth on individual components such as base fuels or specific vehicle types like electric vehicles. Ultimately, many of these assessments point out that a more holistic assessment is needed to place these individual water consumption factors in context of their applicable region or network. Based on this, the main goal for this thesis is to bring these water consumption factors – for fuels, vehicles, and infrastructure – together within the perspective of any given mobility network and compare their overall water consumption against local resource availability and future network trends. This leads to the core research question:

Given the water impacts for individual transportation modes and components, what is the water consumption for a multi-modal, multi-vehicle, and multi-level urban transportation or mobility network?

Of course, assessing an entire transportation or mobility network in terms of water consumption involves considering all applicable factors and parameters. In addition to the water consumption factors that are attributed to individual fuel production and electricity generation, there are numerous water consumption factors stemming from the development and maintenance of road systems, support facilities, and many other elements in our network of interest. As noted in the initial research questions for this thesis, we also need to consider network factors that may indirectly or directly affect water consumption on a top-level basis or on an individual mode. Some of these factors include the network metrics discussed in Chapter 1, such as vehicle miles traveled, average commuting distance, congestion factors, road lengths, number of stations, accessibility, and many more. That said, including every single network parameter – including measurements that may not affect water consumption significantly or at all – would detract from the focus on variables or factors that would pose threats or risks to local water resources. For example, considering every single water consumption component in transportation fuels or energy sources within a region that imports all or most of its fuels would result in an inaccurate outlook of transportation water-related consumption, while a network scenario without any consideration for congestion-related parameters would have a similarly exaggerated overview of localized water consumption. This leads to the first sub-question based off of our core question, which is:

What aspects and indicators of a mobility network's transportation modes or infrastructures are relevant to our assessment of overall water consumption for that network?

Even if we narrow down the most relevant water consumption components and network indicators/metrics, these components need to be structured or represented in a way such that the entire water consumption for a given mobility network can be assessed while monitoring and examining individual consumption factors or metrics. This is of particular importance when attempting to determine the most water-intensive transportation modes or infrastructural components within a transportation system, as well as in assessing various urban regions or alternative scenarios where each region has a unique set of factors ranging from the amount of extra time or fuel consumption from local traffic or congestion to the inclusion of renewable energy sources for electricity generation or alternative fuels and their corresponding modes. Ultimately, we are left with multiple complex levels of water consumption factors that need to be organized into a suitable framework without losing any details pertaining to individual water impact assessments or spatially explicit parameters. Thus, the next sub-question is the following:

How can multiple levels and scales of water impacts for a given mobility network be assessed from a top-level perspective without losing significant component or spatial explicitness and detail? Furthermore, how can these individual components be monitored throughout the assessment?

The gist of this overall research question is not necessarily groundbreaking – in fact, many others have asked very similar questions in managing resources or allocating information on environmental impacts for any system, such as in analyzing greenhouse gas emissions for a given transportation region. The most feasible direction to take in this assessment is to develop or apply some formalization and framework of individual water consumption factors and network or infrastructural parameters for any given urban mobility network such that network stakeholders such as policymakers can gauge the effects of network expansion on water resources.

2.3. Hypothesis for This Thesis

The gist of this overall research question is not necessarily groundbreaking – in fact, many others have asked very similar questions in managing resources or allocating information on environmental impacts for any system, such as in analyzing greenhouse gas emissions for a given transportation region. The most feasible direction to take in this assessment is to develop or apply some formalization and framework of individual water consumption factors and network or infrastructural parameters for any given urban mobility network such that network stakeholders such as policymakers can gauge the effects of network expansion on water resources.

That said, few – if any – assessment frameworks exist for analyzing water resources for a given region or locality, especially within the realm of transportation, and fewer assessments provide some framework that allows for key stakeholders to trace multiple levels of water consumption. Some models, such as the GREET model, assess overall environmental impacts based on user-defined inputs of individual fuels, but leave out water consumption and infrastructural components in its regional assessments, while other models focus mainly on resource inputs based on regional economic activity (Wang, 2010). Ultimately, few structures exist for providing a traceable, repeatable assessment of multi-level water impacts, which leads to the next sub-question:

What methodology or framework is appropriate for combining multi-level and multi-modal water consumption inputs for a given mobility network?

While having any structured approach would allow a formalization of individual water consumption factors and network parameters and facilitate a comprehensive analysis of transportation impacts on local water resources, a traceable, repeatable framework is necessary in order to analyze multiple scenarios based on corresponding sets of system requirements and parameters. One such framework that can be applied to the core research question for this thesis is the Model-Based Systems Engineering approach, which is “the formalized application of modeling to support systems requirements, design, analysis, verification and validation activities” for a product or system’s entire lifecycle from conceptual development to testing (INCOSE, 2007). Ultimately, MBSE advocates that in lieu of conventional systems engineering processes that are document-centric and primarily qualitative in nature, a traceable system model (or models) can be created to illustrate connections and relationships between individual components in a system and to share such knowledge across multidisciplinary development groups. A standard practice in mechanical systems design for some time, MBSE has been proven to enhance development team communication, design precision, and improved integration of systems (Friedenthal et al, 2008). Given its above broad description, Model-Based Systems Engineering principles are potentially effective in combining system-level requirements and components – in the case of this thesis, individual water consumption factors and mobility indicators for a given region – into a framework that is repeatable, traceable, and verifiable for analyzing and testing numerous alternatives or scenarios. Thus, it is hypothesized that **model-based systems engineering can be used to develop a traceable, repeatable model for assessing multi-level and multi-modal water consumption impacts for any given urban mobility network.**

That said, MBSE principles represent a general direction in which overall mobility network water inputs and consumption can be analyzed. A model is not possible ore realizable without modeling tools or a defined specification, and in order to verify that MBSE is indeed a feasible methodology to carry out this analysis, we need to consider the tools – descriptive or analytical – that are necessary to implement this systems model. One such specification that employs MBSE principles is the Systems Modeling Language (SysML), which is a "general-purpose graphical modeling language that supports the analysis, specification, design, verification, and validation of complex systems" and can represent the structural framework, connections, and multi-level parameters of any given system (Friedenthal et al, 2008). The graphical nature of SysML allows for the traceability of individual system components and associated interactions and activities and capturing necessary requirements and parameters. Furthermore, SysML can be interfaced using several analysis tools, such as ParaMagic/Mathematica, MATLAB, or ModelCenter, such that trade studies, optimization, or other engineering analyses can be conducted in order to select a preferred model configuration or scenario. Additionally, previous research has suggested that SysML indeed can provide a traceable and spatially explicit framework of sustainable systems; with the proper implementation of SysML on individual water consumption components and infrastructural parameters, it is believed that a comprehensive assessment on network water consumption for multiple scenarios and regions can indeed be achieved.

Thus, it is proposed for this thesis that **the aggregate water consumption for any given multi-modal and multi-level urban transportation network can be assessed through the use of a structured system model supported by Model-Based Systems Engineering principles and the Systems Modeling Language (SysML), as they can provide a repeatable, spatially explicit framework for such analyses.**

CHAPTER 3

BACKGROUND AND LITERATURE REVIEW

3.1. The Water Footprint and the Concept of Virtual Water

Some previous research and life cycle inventories have focused on water consumption on a regional or national scale as well as in certain goods, services, and materials. Many of these studies have focused on the concept of the **water footprint**. Professor Arjen Y. Hoekstra first defined the term “water footprint” in 2002 in order to quantify the amount of water used not only directly from a consumer or producer/manufacture but also from indirect water usage. In other words, the water footprint concept is intended to measure water usage throughout the entire supply chain or life cycle (Hoekstra and Chapagain, 2009, **Figure 2**). The Water Footprint Network specifies that the water footprint of a process or product can be broken down into three main components irrespective of direct or indirect water usage: the green water footprint represents water stemming from rainwater or natural runoff, the blue water footprint represents freshwater resource consumption, while the grey water footprint refers to water required to capture pollutants, or the volume of water that is polluted during the production of said good or service. Ultimately, the water footprint of a commodity or region serves as a key indicator in water usage based on population and associated consumption patterns (Hoekstra and Chapagain, 2007).

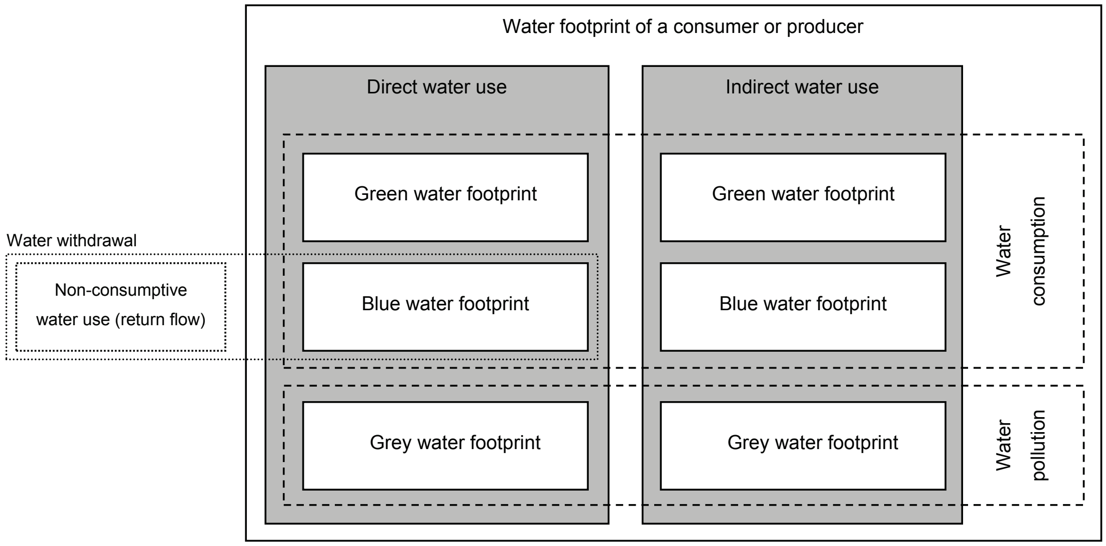


Figure 2. Water Footprint Components Schematic (Hoekstra and Chapagain, 2009).

The water footprint concept is part of a larger context of *virtual water* or *embedded water*, which itself is defined as the total amount of water required to produce a particular good or service. Professor John A. Allan introduced this concept early in the 1990s as part of a broader study in alleviating stressed water resources in the Middle East by importing water-intensive products such as wheat or other food products (Hoekstra and Chapagain, 2007; Allan, 1998). The "virtual" aspect of virtual water stems from that the water used for producing these commodities or services are not actually contained within the products themselves – as such, this concept has led to the idea of a *virtual water trade* in which water-intensive goods and services can be imported from regions with less-stressed water resources to regions that have limited resources. Allan (1998) hinted at this possible trade of water-intensive food crops or other commodities as he examined the lack of conflict over water resources in the Middle East, where he pointed out that many Middle East governments have "obtained the water they need outside their (local) hydrological systems and thus been able to avoid troublesome domestic and regional frictions" via importing food staples from less stressed regions (Allan, 1998).

Allan also points out several priorities for water policies regarding streamlining and optimizing regional water resources ranging from allocating water usage to sectors or products to have the best return to water supplies (otherwise known as allocative efficiency) to investing in more water-efficient management and technology (productive efficiency), although he notes that many governments have been slow to confront political issues regarding allocated efficiency and that these countries need to focus on allocative efficiency in the wake of rising grain prices and diminishing water supplies.

Water footprints have been quantified for commodities ranging from agricultural and bioenergy crops as well as on regional scales. For example, Hoekstra and Chapagain (2007) have assessed and analyzed the aggregate water footprints for a series of countries, from which they examine the internal (domestic) water footprint along with any water footprints from imported commodities or services across agricultural, industrial, and residential/domestic sectors across a selected group of countries ranging from The Netherlands to the U.S. to China. From this assessment, the authors determined that, on a national scale, the total water usage in the United States from 1997 to 2001 was 696 Gm^3 per year (2483 m^3 per capita per year) while the total water consumption for India at the same time period was 987 Gm^3 per year (980 m^3 per capita per year) (Hoekstra and Chapagain, 2007). Based on these values, they found that the water footprint for a specific country or region was dependent on four factors: volume of consumption, consumption pattern, climate, and irrigation; from there, they examined variations between these countries – for example, the higher water footprint per capita in the U.S. was found to be due to large meat consumption and industrial products consumption, while arid regions had higher water footprints due to lower crop productivity and evapotranspiration. Hoekstra and Chapagain also point out several approaches to reducing water footprints for certain regions, such as for adopting less water-intensive production techniques for industrial processes, shifting product consumption patterns (such as reducing meat consumption), and transferring production processes or water-intensive agriculture and livestock from water-stressed regions to countries with abundant water resources.

Other studies have also focused on local comparisons of water usage across cities in different regions. Jenerette et al (2006) used a heterogeneous ecological footprint concept (which assesses the total land area required for ecosystem services) to compare freshwater supplies and usage patterns for a series of cities in both the United States and China based on varying climates, large urban populations, and contrasting economic conditions with the intent of determining key social and environmental variables driving water footprints in these cities and concurrency of these variables and associated trends between American and Chinese cities (Jenerette et al, 2006). These urban water footprints were based both on total freshwater demand for a given city as well as on regional freshwater availability. These cities were selected in order to provide a diverse sample of geographic characteristics and watershed amounts based on data provided from the U.S. Geological Survey and the National Bureau of Statistics of China in terms of annual freshwater supply and per-capita residential water consumption. Using a hierarchical multiple regression analysis, the authors determined that that both sets of cities illustrated the effects of population on freshwater usage equally but that freshwater availability effects were more pronounced in Chinese cities. Ultimately, they determined that while freshwater footprints were not dependent on urban wealth, water footprints in American cities were less variable and greater overall while Chinese city water footprints included more water usage from industrial sectors and were less dependent on urban population. The authors concluded that resource availability was a far more important determinant of urban water footprints than that of urban populations or demographics, and that "understanding the factors that determine urban footprints should provide useful information" for formulating sustainable policies in terms of reduced urban water usage (Jenerette et al, 2006).

That said, while the virtual water concept and its alternative water footprint idea has motivated businesses and regional stakeholders to pursue further studies on quantifying water consumption in their products or services, these concepts rely on several assumptions and also lack an underlying framework such that the idea of virtual water cannot serve as a standalone policy guideline (Wichelns, 2010). For example, Wichelns points out that while the gist of virtual water trade has focused on agricultural and livestock products, these commodities are also heavily dependent on land use and other region-specific characteristics and that trade in these products is driven mainly by productivity instead of solely on water resources. Ultimately, primary stakeholders in agricultural and industrial sectors would have to consider economic, social, and environmental issues in addition to the concept of trading virtual water resources. Furthermore, both concepts have the fundamental assumption that the water resources for each region are the same; in reality, some water-intensive products such as bioenergy or coffee may be produced in regions with abundant direct and indirect water resources, and these findings may also not necessarily reflect external environmental factors such as regional topology, climate, or hydrology.

3.2. Water Consumption in Electricity Generation

In addition to water usage inventories based on the water footprint concept, there have been several studies and inventories focusing on water consumption for electricity generation for certain regions or fuels. The U.S. Geological Survey points out that water usage for thermoelectric power generation represented approximately 39 percent of total withdrawn water in the United States in 2005, which illustrates the significance of the energy sector in a region or country's water usage (Kenny et al, 2009). As such, much effort has been made in quantifying water impacts from power generation as well as to determine possible approaches to reducing water consumption.

Much of this research stems from an investigation into water-energy interdependencies by Peter H. Gleick of The Pacific Institute. Gleick (1994) provided a comprehensive outlook of consumptive water usage for a series of conventional and renewable energy sources in the United States ranging from petroleum and natural gas to hydroelectric and solar power generation. This inventory of water consumption found that water consumption varies greatly with the fuel type and energy source, of which water usage can be attributed mostly to fuel processing and plant operation/cooling, and that water consumption requirements have already begun to inhibit energy production for water-intensive energy systems such as hydroelectric power or ethanol (Gleick, 1994).

Gleick points out that the majority of electricity generation, which stems from thermoelectric, fuel-burning sources such as coal and natural gas, where plant configurations range from once-through cooling processes (where either freshwater or saltwater from large reservoirs can be passed through the plant's cooling systems), to – more recently and in water-scarce regions – closed-cycle wet cooling systems that rely on evaporation from cooling ponds or towers in order to reduce heat output from these plants. Each cooling system, Gleick points out, can be implemented depending on consumptive factors, economic costs, and water resource allocations for the energy sector. Another factor that he points out includes ecological effects from wastewater generated from these plants, as well as the observation that the higher-temperature returned water can pose potential environmental risks to the surrounding ecosystem and water supplies.

In addition to providing a top-level outlook of the water-energy relationship, Gleick also examines water consumption requirements for individual energy fuels or sources. For thermoelectric fuels, he finds that water consumption for thermoelectric fuels can be attributed to mining and extraction, fuel processing, as well as for fuel transport or other miscellaneous processing plant operations (**Figure 3**). Coal, for example, is water intensive in terms of water for surface or underground mining, washing and decontamination, and transport as slurry or by freight train. Similarly, for nuclear fuel, water consumption can be attributed to dust suppression and mining, ore decontamination, as well as uranium milling and enrichment.

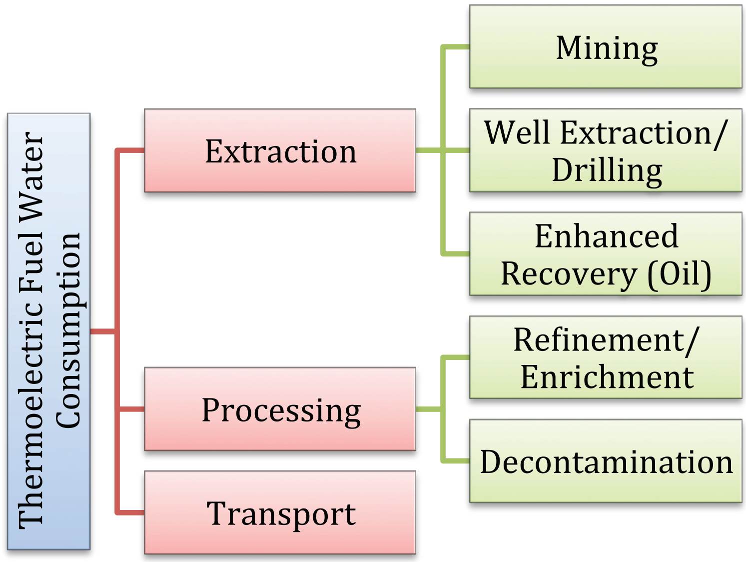


Figure 3. Overview of Water Consumption in Thermoelectric Fuels.

Water consumption for oil and natural gas can be attributed to onshore or offshore exploration and extraction, refining, fuel transport, as well as water required to decontaminate any water extracted from crude oil. While natural gas extraction requires only water for drill coolant, Gleick points out that for crude oil many of the largest and most-accessible fossil fuel reserves have already been emptied – as such, many producers have looked to heavily water-intensive secondary and tertiary recovery methods ranging from water flooding to forward combustion processes in order to increase the amount of recovered crude oil (Gleick, 1994). In addition to water consumption required for fuel extraction and processing, Gleick points out that water is also consumed (in the form of evaporative losses and facility water consumption) in thermoelectric power plants, although for most of these plants have similar water requirements.

Gleick also examines renewable sources such as geothermal, hydroelectric, solar thermal, and wind power. For geothermal sources, he examines feasible systems such as dry-steam and hot water configurations where water consumption is primarily traced to extracted steam or hot water (with some additional water for cooling in some cases);

however, these systems are not widespread. Hydroelectric power water usage is traced mainly to water from reservoirs passed through to drive turbines, although there is a significant amount of evaporative and seepage losses from required water reservoirs depending on the surrounding environment and climate. Gleick does not provide a comprehensive assessment of water consumption for photovoltaic solar and wind power as these sources use negligible amounts of water.

Much of Gleick's research into determining the relationship between water consumption and energy generation has been leveraged or refined in recent years to provide more depth or to raise awareness to regional and national policymakers regarding water requirements for power. A significant amount of water usage data for electricity generation can be found in a 2006 Department of Energy report that analyzes water and energy interdependencies and focuses on any impacts on energy production in areas of limited water resources. Of note, the report examines the water usage within various energy sources across the United States - water that stems from resource extraction, processing, power generation and transportation based on the water-energy relationships summarized in **Table 1** (Merson et al, 2006). However, data is only available on an aggregate, national level: the report estimates that total thermoelectric water consumption was 3.3 billion gallons per day in 1995, while hydropower systems involve 3.16 trillion gallons of water per day in terms of overall flow (this is not listed as withdrawn water, although 3.8 billion gallons are "consumed" via evaporation per day. In terms of coal mining, where water is used to cool drilling equipment, suppress dust, and process fuel, the report uses water intensity values based on energy (1-6 gallons per million Btu) and coal production data from the EIA to determine the total water usage to be at 70 to 260 million gallons per day. In terms of conventional oil and gas, the reports note the presence of "produced" water from extracted oil and gas (2-350 gallons of water per gallon of oil extracted) that can be used for enhanced oil recovery, but gives no data on aggregate water usage from petroleum and gas extraction. Interestingly, the report notes that energy is required for the supplies, purification, distribution, and treatment of water nationwide, illustrating the close interdependence on water resources and energy. Additionally, the report also notes areas of water stress or shortages that could potentially limit conventional electricity generation and propose areas for implementing less intensive systems.

Table 1. Water-Energy Relationships for Fuel and Energy Production (Merson et al, 2006).

Energy Element	Connection to Water Quantity
Energy Extraction and Production	
Oil and Gas Exploration	Water for Drilling, Completion, Fracturing
Oil and Gas Production	Large volumes of produced, impaired water
Coal and Uranium Mining	Mining operations can generate large quantities of water
Refining and Processing	
Traditional Oil and Gas Refining	Water needed to refine oil and gas
Biofuels and Ethanol	Water for growing and refining
Synfuels	Water for synthesis
Electric Power Generation	
Thermoelectric	Surface and ground water required for cooling and scrubbing
Hydroelectric	Reservoirs lose large quantities to evaporation
Solar PV and Wind	None during operation; minimal water use for panel and blade washing
Energy Transportation and Storage	
Energy Pipelines	Water for hydrostatic testing
Coal Slurry Pipelines	Water for slurry transport; water not returned
Barge transport of energy	River flows and stages impact fuel delivery
Oil and Gas Storage Caverns	Slurry Mining of caverns requires large quantities of water

Fthenakis et al (2010) builds upon Gleick's research by providing more of an in-depth analysis of life cycle water usage for both conventional and renewable energy sources. The authors evaluated both direct and indirect (upstream) water usage for the extraction and refinement of thermoelectric (conventional and biomass) fuels, as illustrated in **Figure 4**, as well as for the fabrication and maintenance of renewable energies. From these observations, they noted the greatest lifecycle factors for water usage was in the operation of thermoelectric power plants for conventional fuels and in the acquiring and processing of materials (silicon for PV cells and irrigation for energy crops, for example) for renewable energies or biofuels. Ultimately, they stated that regional water resources are at risk of water shortages due to the addition of upstream water usage in renewable energy sources to the cooling water already used in U.S. power plants; however, they point out that some regions in the United States, such as the Southwest, are abundant in other resources such as solar power that may pave the way for more water-efficient energy source implementation (Fthenakis et al, 2010).

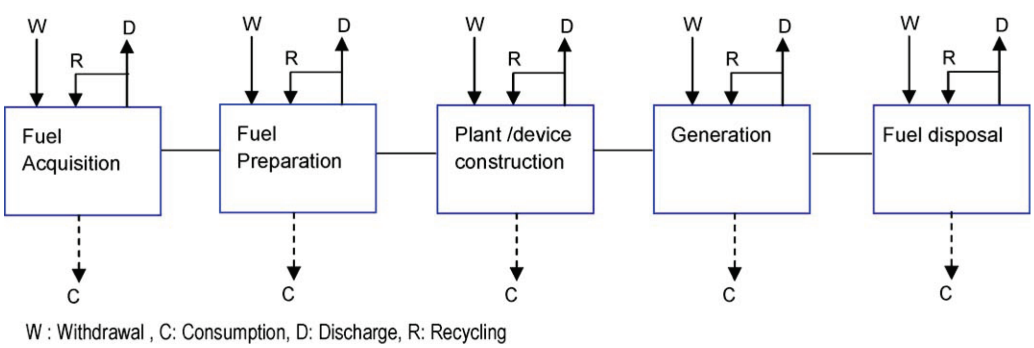


Figure 4. Thermoelectric Fuel Cycle Water Flows (Ftehnakis et al, 2010).

Other studies have focused solely on water consumption for specific power generation methods such as thermoelectric power generation. Feeley et al (2008) focused primarily on water's crucial role in the thermoelectric power industry, where they point out that large quantities of water are withdrawn for power generation, as well as a relatively small amount consumed (at 3 billion gallons per day in the United States total). The authors also distinguish between once through and recirculating cooling systems where water is used to dissipate heat to the atmosphere, and that for the United States

42.7 percent of power plants in the U.S. use once-through systems, 41.9 percent wet cooling towers, and 14.5 percent cooling ponds (Feeley et al, 2008). The authors also used the Energy Information Administration's Annual Energy Outlook 2006 in order to determine water electricity cooling method distributions for 2030 based on status quo, regulation-driven, limited regulation, dry cooling, and conversion scenarios, since it was projected that thermoelectric generation would increase by 22 percent from 2005 to 2030. For all five cases total withdrawal decreases by 0.5 to 30 percent (due to the implementation of recirculating or dry cooling systems) while consumption increases by 21 to 48.4 percent overall, with varying increases in withdrawal and consumption by state or energy sector region.

Table 2. Power Generation Regions and Associated Abbreviations from the Annual Energy Outlook Report (2006) (Feeley et al, 2008).

Region Name	Abbreviation
East Central Area Reliability Coordination Agreement	ECAR
Electric Reliability Council of Texas	ERCOT
Mid-Atlantic Area Council	MAAC
Mid-America Interconnected Network	MAIN
Mid-Continent Area Power Pool	MAPP
Northeast Power Coordinating Council/New York	NPCC/NY
Northeast Power Coordinating Council/New England	NPCC/NE
Florida Reliability Coordinating Council	FRCC
Southeastern Electric Reliability Council	SERC
Southwest Power Pool	SPP
Western Electricity Coordinating Council/Northwest Power Pool	WECC/NWPP
Western Electricity Coordinating Council/Rocky Mountains, AZ, NM, southern NV	WECC/RM
Western Electricity Coordinating Council/California	WECC/CA

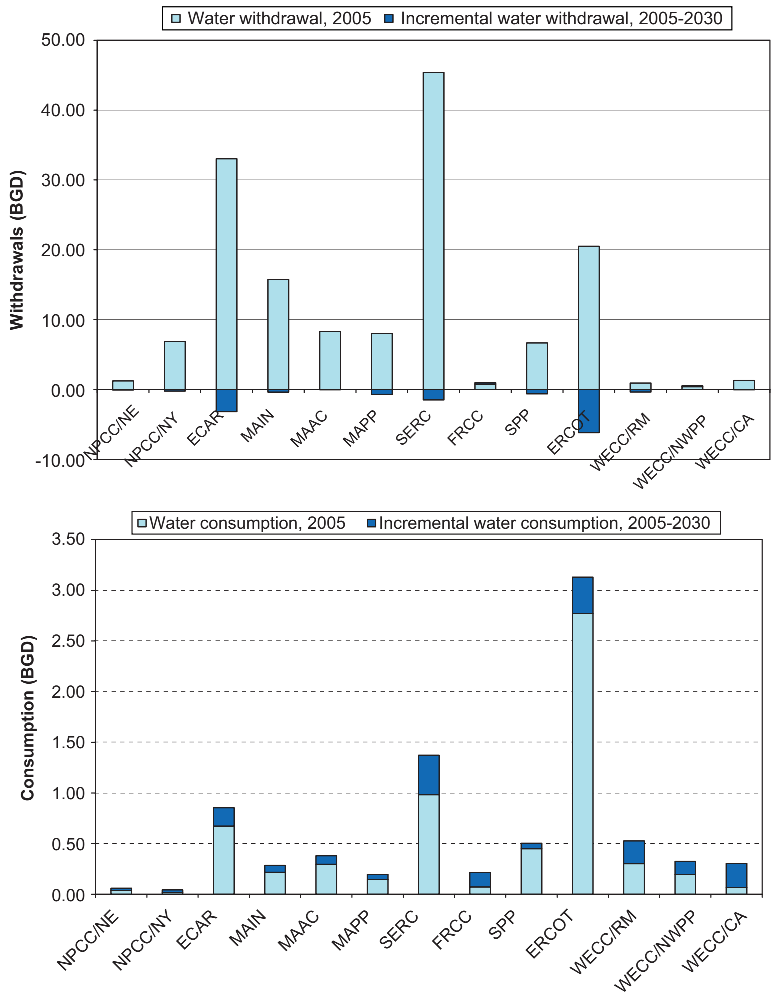


Figure 5. Electricity Sector Water Withdrawals (top) and Consumption (bottom) for 2005-2030 by Power Region (Feeley et al, 2008).

Investigations in water consumption for the energy sector have also been duplicated for regions outside the United States. Carrillo and Frei (2009) compared the amount of water usage within the energy production sector with forecasted future water requirements using a linear model that incorporates the water usage for specific energy generation technologies and regional energy mixes based on available and future technologies in order to determine future and current water demands in Spain. Based on a technology matrix consisting of data collected for total water consumption and withdrawal along with energy production processes, the researchers estimated water requirements within specific regions using a regional scenario vector - in this study, the total energy demand of a given country or locality. As such, in contrast to existing LCAs regarding resource usage in electricity generation, this model only analyzes electricity and fuel production processes within a specific region. The authors broke down the electricity sector into electricity generation for thermal plants and renewable sources as well as the extraction and production of raw fuels; in terms of transportation, the authors considered the refining processes and production of oil or biomass.

In addition to current electricity generation statistics, the authors also use synthesized electricity production forecasts for 2030 (the projected electricity production distribution for 2030) as well as for biofuel-dominated electricity production and wind-dominated production; all of these scenarios were analyzed using the linear model and compared to the electricity mix for 2005. Using the model, the authors determined that the 2030 electricity generation prediction would have less withdrawn water but 25 percent more consumed water (due to the inclusion of biofuels), while the inclusion of more biofuels to the transportation sector would increase current transportation water consumption by four times. When considering a biofuel-dominated energy and transportation sector, water consumption in transportation would be four times greater than that of water consumption in electricity generation. From this, the authors point out that a more ideal electricity mix would be dominated by wind power and other renewable technologies (for hydropower, water would be lost through evaporation but in terms of withdrawal renewable energies would withdraw only 25% of the water withdrawn for current electricity production. Of note, the authors point out that water consumption data was synthesized from reports carried out in other countries due to the lack of reliable or consistent data in Spain; despite this drawback, the regional model provides a potential approach to the localized system model for urban or regional transportation networks.

Water consumption values for electricity generation can also be broken down by state or region, where variations in water consumption are due to environmental differences such as changes in temperature (Torcellini et al, 2003). Water consumption for thermoelectric power plants was calculated by accounting for water losses in terms of percentages of total water withdrawals, where it was noted that fresh water consumptive use is greater in plants that use cooling towers or ponds compared to those that solely withdraw water from local resources and return grey water to the surrounding environment. For hydroelectric water consumption, much of the consumptive use can be traced to evaporative losses via accounting for the total amount of water from hydroelectric reservoirs as a function of produced energy across an inventory of hydroelectric dams in the United States; however, Torcellini et al (2003) note that many dams provide multiple functions and not all evaporation can be traced solely to power plant generation. In other words, “there is no easy way to disaggregate on a national level the end uses of hydroelectric dam water into irrigation, flood control, municipal water, and thermoelectric power plant cooling” (Torcellini et al, 2003).

3.2.1. Discussion

The above studies pertaining to water consumption and usage in electricity generation show the widespread dependency of electricity generation and energy production on local or foreign water resources. Water is consumed in the production of all thermoelectric fuels as shown in Gleick (1994), where such water consumption inputs can generally be divided into water consumed in extracting or mining raw materials, refining these materials into usable fuels, and distributing or transporting these fuels; this division in total water consumption can also be seen in allocating water consumption for biofuels as shown later on. These water consumption values for thermoelectric fuels can be summarized below in **Table 3**.

Table 3. Summary of Water Consumption Values for Thermoelectric Fuels (Adapted from Gleick, 1994).

Fuel	Process	Sub-Process	Technology	Water Consumed (low), L/GJ	Water Consumed (high), L/GJ	Average Water Consumed, L/GJ
Coal	Mining	Surface		2	5	
		Underground		3	20	
	Processing	Beneficiation				4
	Transport	Slurry Pipeline		40	85	
	Gasification			35	70	
	Liquefaction			40	95	
Uranium	Mining	Open Pit				20
		Underground				0.2
	Processing	Milling		8	10	
		Conversion	Uranium Hexafluoride			4
		Enrichment	Diffusion	11	13	
			Centrifuge			2
			Fabrication			1
Natural Gas	Processing	Purification				6
	Transport	Pipeline				3

Furthermore, significant amounts of water consumption are required for electricity generation; as discussed in these assessments, water is primarily consumed in power plants due to operation and scrubbing or for steam generation. For hydroelectric power generation, water is consumed through evaporative losses from reservoirs, although these evaporative losses are not necessarily allocated solely to power plant generation. Improvements in power plant cooling technologies such as in the implementation of cooling towers allow these plants to withdraw less water but ultimately increase consumptive water usage where more water is lost from evaporation or seepage. Further improvements in power plant cooling can effectively eliminate any water consumption from power plants altogether through the inclusion of dry cooling technologies that use air instead of water for steam cooling and condensation. On the other hand, non-hydroelectric renewable electricity generation sources consume little to no water as water is used mainly for operation and maintenance in these sources. Water consumption values for specific power plant technologies are summarized in **Tables 4 to 7** for thermoelectric power plants and **Table 8** for renewable electricity generation.

While the focus of this review will be on water consumption for electricity generation, overall water usage (including water withdrawals from a local source) represents an even larger set of flows for power plants and fuel production. These tables are shown in **Appendix B.1.5**.

Table 4. Summary of Water Consumption Findings for Coal-Fired Power Plants By Configuration/Technology (Various Sources).

Fuel	Cooling Config	Boiler Type	FGD Type	Water Consumed, gal/kWh	Water Consumed, l/kWh	Reference
Coal	Once-Through	Subcritical	Wet	0.138	0.522	Feeley et al, 2008
			Dry	0.113	0.428	
			None	0.071	0.269	
		Supercritical	Wet	0.124	0.469	
			Dry	0.103	0.389	
			None	0.064	0.242	
	Cooling Tower	Subcritical	Wet	0.462	1.749	
			Dry	0.437	1.654	
			None	0.394	1.492	
		Supercritical	Wet	0.518	1.961	
			Dry	0.496	1.878	
			None	0.458	1.733	
	Cooling Pond	Subcritical	Wet	0.804	3.043	
			Dry	0.779	2.949	
			None	0.737	2.789	
		Supercritical	Wet	0.064	0.242	
			Dry	0.042	0.159	
			None	0.004	0.0151	

Table 4 (continued).

Fuel	Cooling Config	Boiler Type	FGD Type	Water Consumed, gal/kWh	Water Consumed, L/kWh	Reference
Coal	Once-Through	Subcritical	NETL Projections 2009		0.53	Fthenakis et al, 2010
		Supercritical	EPRI Projections		0.45	
		N/A	NETL Projections 2009		1.14	
			Gleick, 1994		1.21	
					0.95	
	Cooling Pond	Subcritical	NETL Projections 2009		3.03	
		Supercritical			0.24	
		N/A	EPRI Projections		1-1.9	
	Cooling Tower	Subcritical	NETL Projections 2009		1.74	
			NETL Baseline 2007		2.56	
			NETL 2005 Study		4.43	
		Supercritical	NETL Projections 2009		1.97	
			NETL 2005 Study		3.94	
			NETL Baseline 2007		2.24	
	Cooling Tower		EPRI Projections		1.7-1.9	
			Gleick, 1994		3.1	
			DOE 1983		2.8	
					1.9	
	Cooling Tower		Conventional		2.6	Gleick, 1994
			Fluidized-Bed		0.8	
	Once-Through		Conventional		1.2	
IGCC Coal	Cooling Tower		NETL Projections 2009		0.655	Fthenakis et al, 2010

Table 5. Summary of Water Consumption Findings for Nuclear Power Plants By Configuration/Technology (Various Sources).

Fuel	Cooling Configuration	Technology	Data Sourcing	Water Consumed, L/kWh	Reference
Nuclear	Once-Through			0.519	Feeley et al, 2008
	Cooling Tower			2.362	
	Cooling Tower	LWR		3.2	Gleick, 1994
		HTGR		2.2	
	Once-Through		NETL 2009	0.53	Fthenakis et al, 2010
			EPRI	1.5	
	Cooling Pond		EPRI	1.7-3.4	
	Cooling Tower		NETL 2009	2.3	
			EPRI	2.8-3.4	
		PWR	DOE 1983	3.1	
		BWR		3.4	

Table 6. Summary of Water Consumption Findings for Oil and Natural Gas Power Plants By Configuration/Technology (Various Sources).

Fuel	Cooling Configuration	Data Sourcing	Water Consumed, L/kWh	Reference
Oil or NG	Once-Through		0.341	Feeley et al, 2008
	Cooling Tower		0.606	
	Once-Through		1.1	Gleick, 1994
	Cooling Tower		2.6	
	Once-Through	NETL 2009	0.341	Fthenakis et al, 2010
		DOE 1983	0.95	
	Cooling Pond	NETL 2009	0.42	
	Cooling Tower	NETL 2009	0.61	
		DOE 1983	1.1	
NGCC	Once-Through	NETL 2009	0.076	Fthenakis et al, 2010
		EPRI	0.38	
	Cooling Pond	NETL 2009	0.91	
	Cooling Tower	NETL 2009	0.49	
		NETL 2007	1.02	
		NETL 2005	1.9	
		EPRI	0.68	
	Dry Cool	NETL 2009	0.015	
	Once-Through		0.00758	Feeley et al, 2008
	Cooling Tower		0.492	
	Cooling Pond		0.908	
	Dry Cool		0.0151	

Table 7. Summary of Water Consumption Findings for Biomass Power Plants By Configuration/Technology (Various Sources).

Biofuel	Cooling Config	Data Source	Water Consumed, L/kWh	Reference
Wood Waste	Cooling Tower		2.3	Gleick, 1994
Biomass	Steam Plant	Berndes, 2002	1.8	Fthenakis et al, 2010
	Cooling Tower		1.7	
	Dry Cool		0	

Table 8. Summary of Water Consumption Findings for Renewable Power Plants By Region and Technology (Various Sources).

Plant	Location	Water Consumed, L/kWh	Reference
Hydro	United States Avg	17	Gleick, 1994
	California Median	5.4	
	California Mean	26	
	Western Interconnect	47	Torcellini et al, 2003
	Eastern Interconnect	208.5	
	Texas Interconnect	0	
	United States Avg	68	
PV Solar	Central Utility	0.1	Gleick, 1994
	Utility Operation/Maintenance, Low	0.023	Harto et al, 2010
	Utility Operation/Maintenance, High	0.0757	
	United States Avg	0.015	Fthenakis et al, 2010
Wind		0.004	Fthenakis et al, 2010
		0	Gleick, 1994

Another interesting direction posed in some of these assessments pertain to forecasting water consumption values based on projected electricity generation requirements and amounts in the near future, such as in Carrillo et al (2009) and Feeley et al (2003), where electricity generation estimates for 2030 are calculated from existing models and datasets such as the Annual Energy Outlook report of electricity share projections for each grid region in the United States. These projections in electricity generation can also be combined with technological projections where more efficient plant configurations such as high-temperature gas reactors for nuclear power plants and coal gasification in place of conventional coal-fired power plants so that potential future impacts on water resources with respect to electricity generation – and possibly vehicle usage – can be determined (Goldstein and Smith, 2002).

3.3. Water Demands for Bioenergy

Water footprint research has also focused on specific groups of commodities such as for bioenergy. Gerbens-Leenes et al (2009) examined biomass crops in terms of energy crops, food crops, and organic waste for either transportation biofuels such as biodiesel and ethanol or biomass for energy generation, which accounts for approximately 86 percent of worldwide freshwater usage (Gerbens-Leenes et al, 2009; Hoekstra and Chapagain, 2007). The water footprints for these crops, ranging from sugar cane to rapeseed, were determined across The Netherlands, the U.S., Brazil, and Zimbabwe by analyzing daily crop evapotranspiration for each of these crops and locations; these water footprint calculations were then directly compared against established water consumption figures for conventional energy sources and fuels. In general, the authors determined that maize had the smallest water footprint for all countries except Zimbabwe (where sugarcane had the smallest water footprint), while rapeseed (for biodiesel) and cotton had the largest associated water usage overall; overall, across food and energy crops, there was no significant difference in terms of overall water footprint. On average, the water footprint for bioenergy crops was 24 cubic meters per GJ in The Netherlands as opposed to 57 cubic meters in the U.S. and 142 cubic meters in Zimbabwe – in contrast to a maximum of 1.1 cubic meters per GJ required for conventional energy carriers (Gerbens-Leenes et al, 2009). Ultimately, these findings suggest that a switch to bioenergy or hydropower from primary energy sources such as natural gas or coal would result in a substantially larger amount of water usage, especially for low-yield crop regions such as Brazil and Zimbabwe, where the increase in water usage can range from 70 to 400 times that of conventional energy sources, and that further strategies for implementing these energy sources need consider such increased footprints and potential causes for energy-food water conflicts.

In terms of including bioenergy as a potentially widespread energy source in the future, Berndes (2002) analyzes the implications of large-scale substitution of biofuels for fossil fuels in terms of water consumption and withdrawal by estimating the amount of water required to grow and produce biofuels for transportation or electricity use, from which he determines whether regional or global water resources are sufficient for such transplantation. Noting that the majority of water consumption for biomass is attributed to evapotranspiration losses in energy crops, Berndes estimates a 30 percent more water withdrawal to present and future withdrawal averages and uses such forecasts to simulate potential impacts (due to the inclusion of biofuels to the energy and transportation sectors) to water resources across the world (Berndes, 2002). This was applied to several countries of varying water demands and resource availability, where he noted that bioenergy production would not affect water resources in Canada, Russia, Indonesia, and Brazil (which already has a biofuel production structure) but would cause additional stress in water-scarce regions. That said, the author notes via a sensitivity analysis that the study was done uniformly and only provides indications of forecasted changes across the world, and that there is much uncertainty in terms of the extent of irrigation in energy crops and associated evapotranspiration.

3.4. Water Consumption in Transportation Fuels

In addition to research into water consumption and withdrawal, several studies have assessed the amount of water used in fuels used for transportation ranging from conventional gasoline to biodiesel as well as to electricity for battery electric vehicles.

Several studies and assessments have examined water impacts in conventional and alternative fuels such as petroleum gasoline, natural gas, and biofuels such as biodiesel and ethanol for various feedstock crops.

3.4.1. Water Consumption for Petroleum Gasoline

The first major life cycle water assessment for petroleum-based fuels was conducted as part of the comprehensive energy-water outlook as described in Gleick (1994), where Gleick assessed water demands for the extraction and refining processes for crude oil and petroleum. Water consumption was calculated for onshore exploration and primary extraction, as well as for secondary and tertiary methods including enhanced oil recovery (EOR) technologies, as well as for petroleum refining; these results were summarized previously in **Table 2**.

That said, while Gleick's water consumption data for petroleum extraction and refinement illustrate the widely varying water requirements for producing gasoline and diesel, there is no information regarding the distribution of these technologies in fuel production pathways in the United States. A more recent study from Wu et al (2009) provides a more detailed breakdown of available fuel extraction technologies based on the process water flows described in **Figure 6,** from which a weighted average of primary and additional oil extraction water consumption could be determined (and by extension a comprehensive range of total water consumption for gasoline production) (Wu et al, 2009). This recent study outlines the technology shares in onshore and offshore crude oil extraction in key production regions in the United States, as shown in **Figure 7**. In this assessment, the authors considered three major petroleum-producing regions in the

United States that contribute to 90 percent of domestic crude oil production and 81 percent of oil refining.

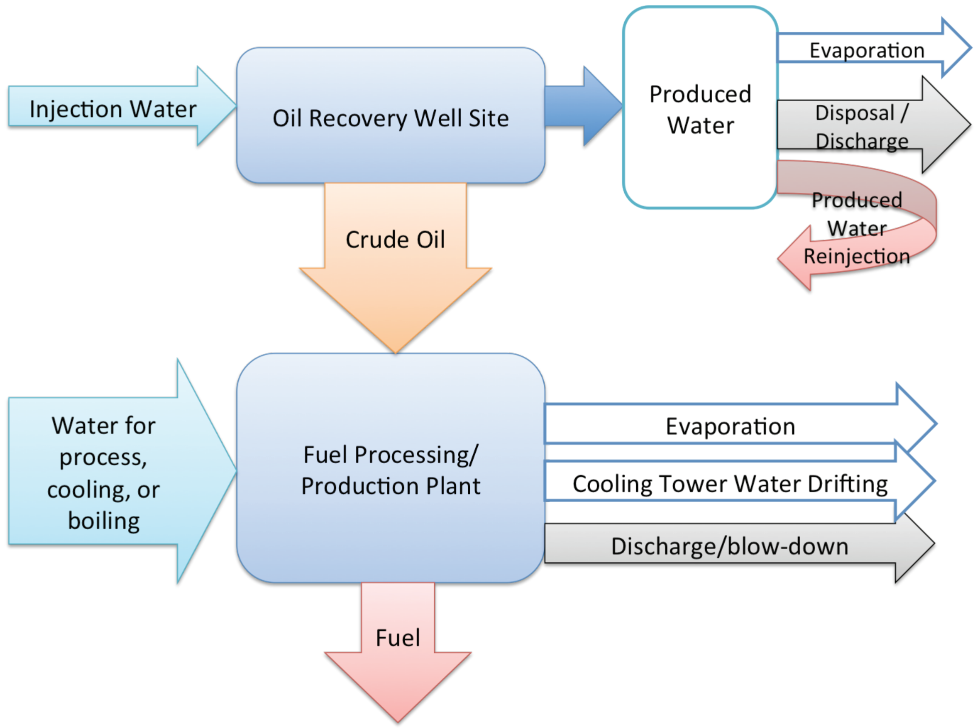


Figure 6. Water Inputs and Outputs for Petroleum Production (Adapted from Wu et al, 2009).

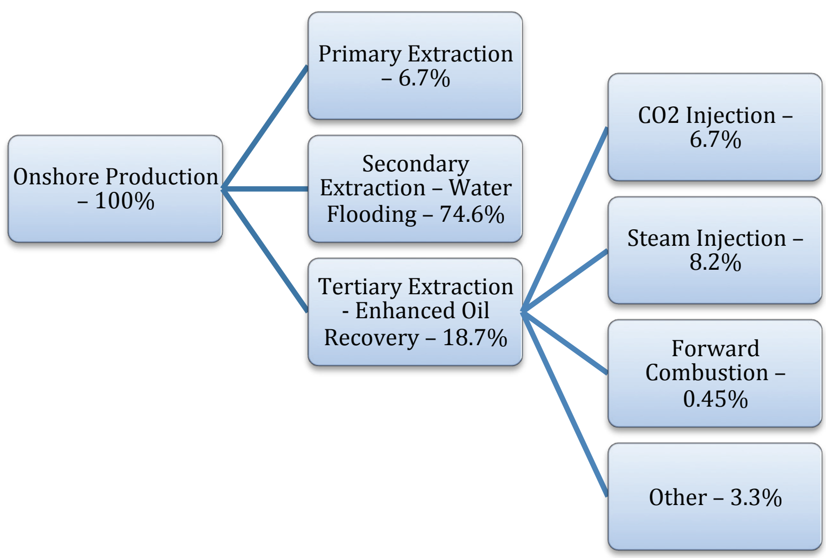


Figure 7. Technology Distribution For Onshore Oil Production (Adapted from Wu et al, 2009).

In addition to specifying the distribution of primary and secondary oil recovery technologies in these regions, the researchers also examine the amount of produced water stemming from water stored in extracted crude oil that needs to be removed from the extracted fuel; some of the produced water is reintroduced to the well via water flooding and injection in secondary recovery methods, which is included in the net water consumption estimate of petroleum extraction of 2.1-5.4 liters of water per liter of product. This is combined with the above refining water consumption range stated in the previous study to obtain an aggregate range of 5.4 to 7 liters of water per liter of gasoline.

In addition to assessing domestic crude oil production, the authors also considered foreign oil production by examining water consumption trends in Saudi Arabian oil production, as that region has a lack of surface water and low recharging aquifer rates (Wu et al, 2009). Much of the water used in the oil production process in Saudi Arabia is treated from brackish or seawater resources, and the authors stress that water consumption values are based on individual wells and projects instead of a national distribution. Similarly, the authors considered petroleum recovered from Canadian oil sands, which accounts for 39 percent of total petroleum production in Canada, from where bitumen is either extracted from surface mining or in situ extraction methods and is processed into synthetic crude oil; as with EOR technologies for conventional crude extraction, the authors assessed water demands based on a national technology distribution for oil sands production. Water consumption for oil sands crude production was leveraged from Gleick's study (which includes a brief assessment of oil sands crude production) and later assessments for surface mining and in situ oil sands extraction. These water consumption values are summarized below in **Figure 8** and **Table 9,** where a direct comparison shows that water consumption varies significantly based on regional conditions for conventional crude extraction, while water consumption in Saudi Arabian and Canadian oil sands production are slightly lower overall.

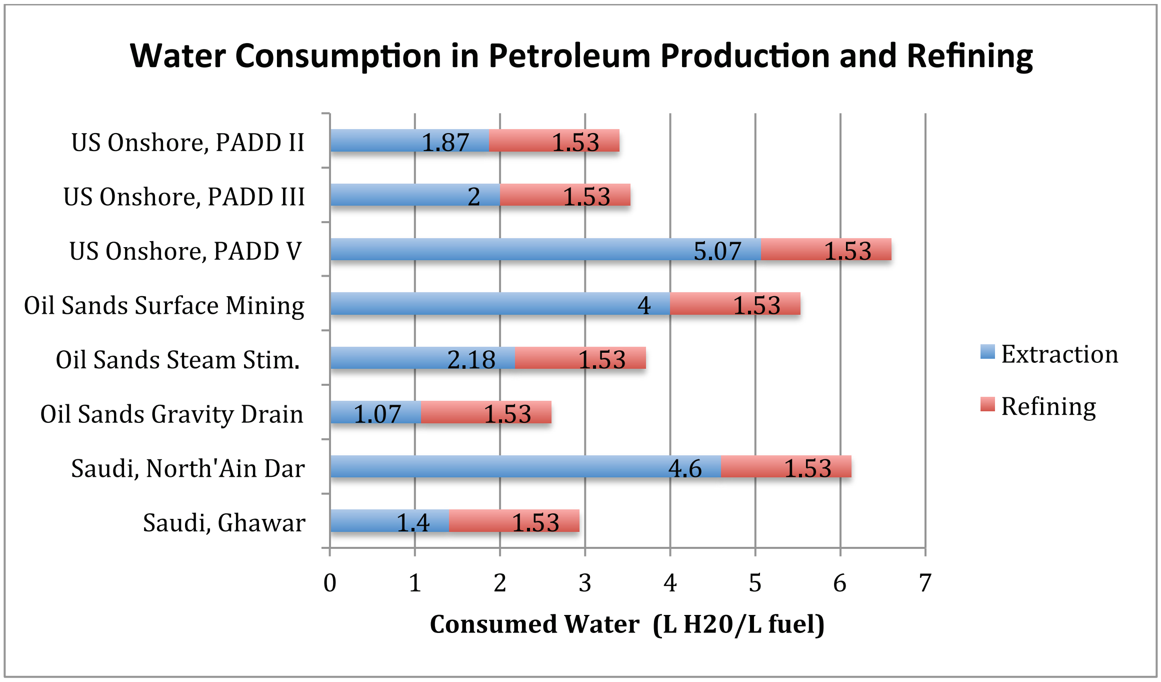


Figure 8. Water Consumption for Petroleum Production and Refining for U.S., Canadian, and Saudi Production (Adapted from Wu et al, 2009).

Table 9. Water Consumption Summary for Gasoline Production (Wu et al, 2009).

Fuel Pathway	**Low Water Consumption (L/L)**	**High Water Consumption (L/L)**
U.S. Onshore Production/Refining	3.4	6.6
Canadian Oil Sands	2.6	6.2
Saudi Arabian Production/Refining	2.8	5.8

Another comprehensive life cycle assessment focuses on petroleum diesel production for a public transit bus. Sheehan et al (1998) examined resource inputs for crude oil extraction, refining, and intermediate transportation based on domestic and foreign crude oil production as well as for onshore, offshore, and enhanced recovery methods. Material input, energy and equipment usage, and emissions were allocated for conventional and enhanced (EOR) onshore and offshore extraction, with key material inputs for conventional extraction being crude oil and natural gas produced from oil recovery, with outputs including volatile organic compounds (VOCs), waste and water effluents, co-produced natural gas, and emissions. Additionally, in terms of energy and equipment usage, the authors assumed that energy generated for oil extraction and oil separation stems from natural gas produced from that source. Inputs and outputs for conventional onshore and offshore extraction are summarized below in **Figures 9 & 10** and **Table 10** (Sheehan et al, 1998).

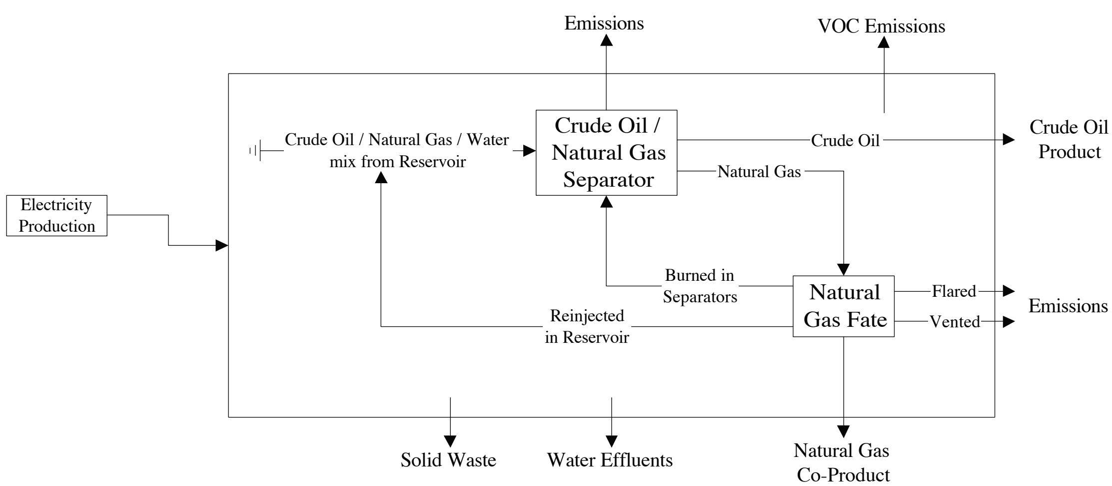


Figure 9. Conventional Onshore Crude Oil Extraction Modeling (Sheehan et al, 1998).

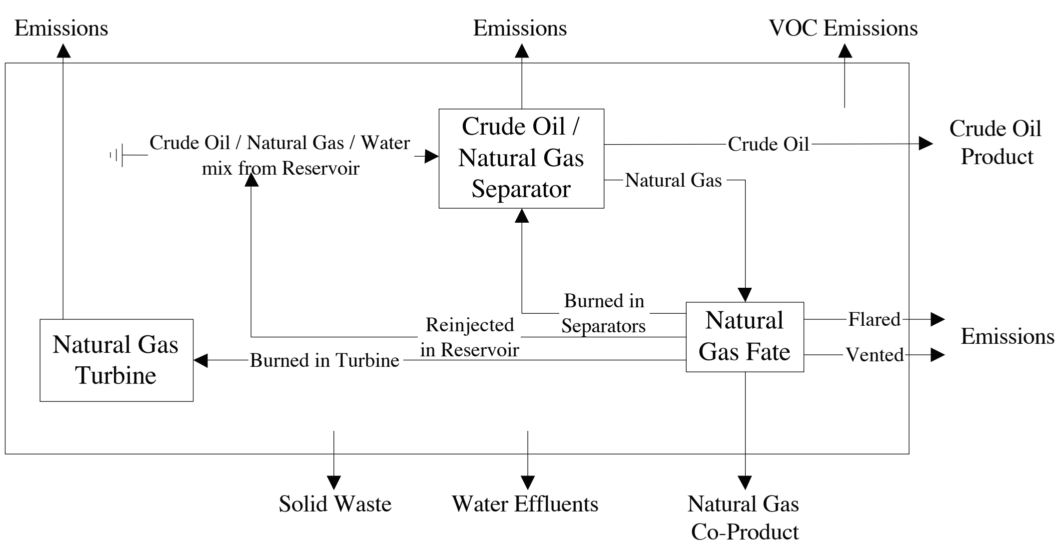


Figure 10. Conventional Offshore Crude Oil Extraction Modeling (Sheehan et al, 1998).

Table 10. Water Inputs for Domestic & Foreign Crude Oil Extraction (Sheehan et al, 1998).

Process Configuration	Water Used, l/l crude oil	Water Used, l/l crude oil
Onshore, Conventional	0.0003	2.5E-04
Offshore, Conventional	0	0
Onshore, Enhanced Recovery (Carbon Dioxide and Steam Injection)	0.2214	0.184
Domestic Total	**0.2217**	**0.1845**
Foreign Onshore, Conventional	0.0003	2.7E-04
Foreign Offshore, Conventional	0	0
Foreign Onshore, EOR	0.0604	0.0502
Foreign Total	**0.0607**	**0.505**

While Wu et al (2009) and Gleick (1994) examined water consumption for all viable configurations of enhanced oil recovery technologies (as well as a technology distribution of these configurations), Sheehan et al (1998) focused mainly on enhanced oil extraction using steam and carbon dioxide injection technologies. As with the above material input pathways for conventional extraction, the authors noted crude oil, natural gas, and associated produced electricity as material inputs for steam-injected extraction, while carbon dioxide production is an additional input for CO_2 injection; notably, the authors point out that process emissions from steam and carbon dioxide injection do not include wastewater. As with the previous two assessments on water usage in crude oil extraction, enhanced oil recovery processes use significantly more water than in conventional extraction processes – up to three orders of magnitude higher than that of conventional/primary extraction methods. Interestingly, foreign crude oil extraction involves similar amounts of water usage for conventional processes and significantly less water used for enhanced recovery processes, which is a similar trend seen in Wu et al (2009) (Sheehan et al, 1998).

In addition to total water usage in crude oil extraction, Sheehan et al (1998) examined material inputs and emissions for a crude oil refining process for diesel as summarized below in **Figure 11**. Unlike the regional considerations made in Wu et al (2009), the authors in this assessment utilized national average performance in allocating material flows and inputs for crude oil refining based on a mass and energy balance. Material flows specified in this assessment included crude oil and other petroleum-based liquids and unfinished oils, as well as steam, natural gas, coal, propane, coke, and electricity for the refining process.

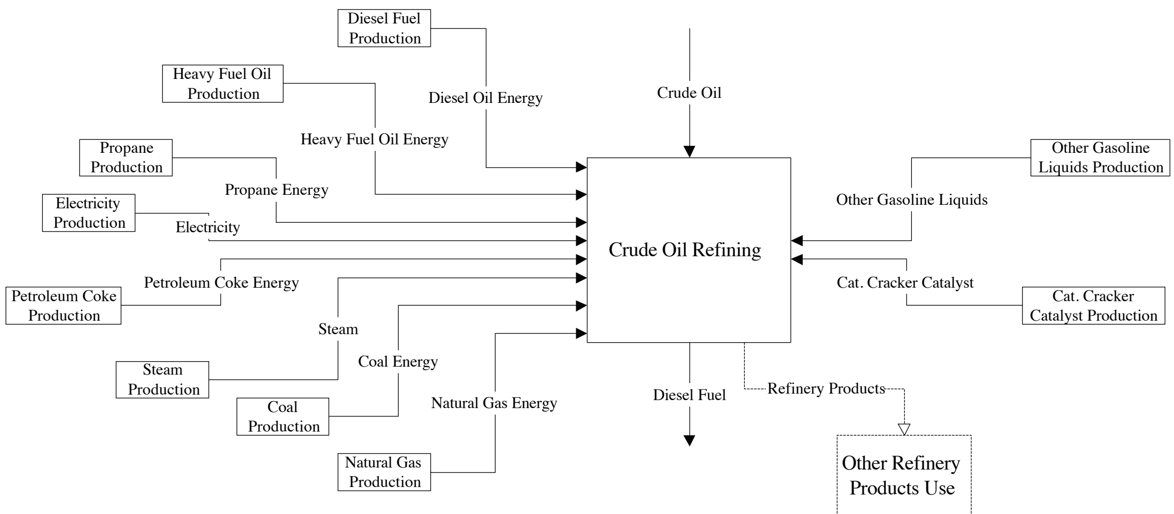


Figure 11. Crude Oil Refining Process Flows (Sheehan et al, 1998).

In addition to the extraction and refining processes in the fuel production life cycle, the authors also focused on intermediate transportation of crude oil and diesel fuel for pipeline, tanker, or truck transport. For crude oil transportation, the authors considered domestic tankers and barges with distances based on national averages in addition to pipeline transportation where crude oil is transported directly to refineries. Material inputs and emissions were primarily calculated from the loading of crude oil to and from road and rail vehicles and associated fuel consumption; for tanker transport from domestic and foreign sources, the authors considered the same inputs and outputs from loading and unloading tankers. Additionally, for loading and unloading, the authors considered electricity required for pumping fuel to and from these vehicles. For diesel fuel transportation, the authors also considered material inputs and emissions from intermediate fuel storage and handling.

Total water usage values for all of the assessed processes in diesel fuel production are summarized below in **Figure 12**, where the vast majority of water usage is traced to crude oil extraction.

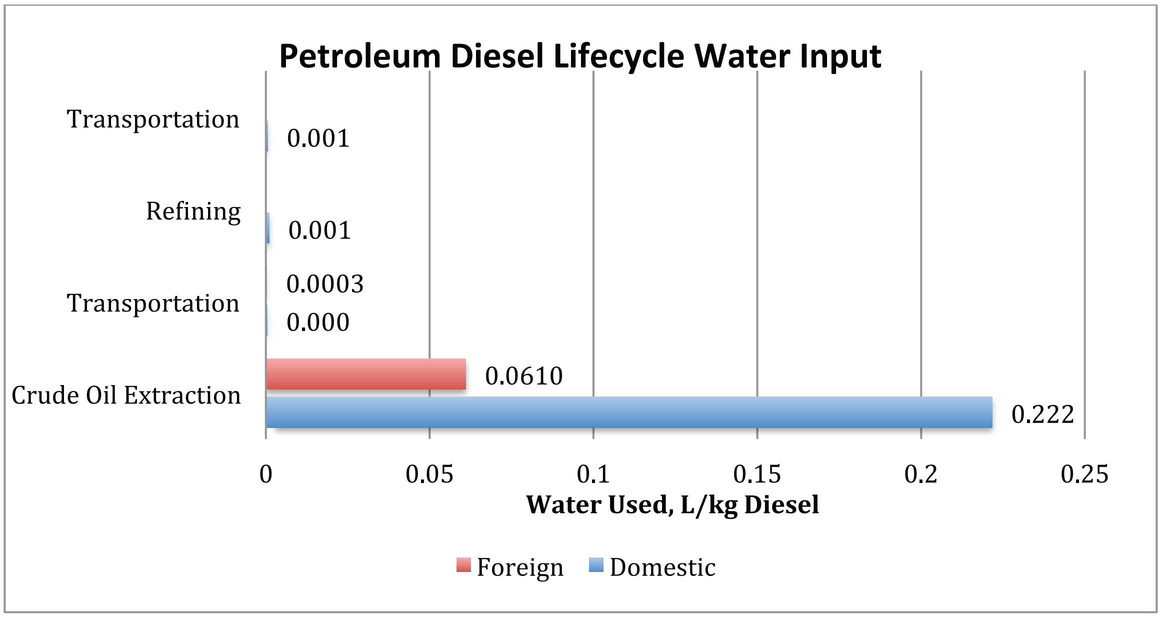


Figure 12. Life Cycle Water Usage for Diesel Production (Adapted from Sheehan et al, 1998).

3.4.2. Water Consumption for Ethanol

Recent studies have been conducting in assessing the lifecycle water impacts of biofuels such as ethanol and biodiesel. Ometto et al (2009) performed a life cycle assessment of ethanol production from sugarcane in Brazil in an attempt to analyze environmental impacts and their causes (associated production processes) and to provide approaches to mitigate these impacts. The authors presented a comprehensive assessment into the processes and associated resources (renewable and non-renewable) of which water usage is one of the quantities considered (**Figure 13,** Ometto et al 2009**)**.

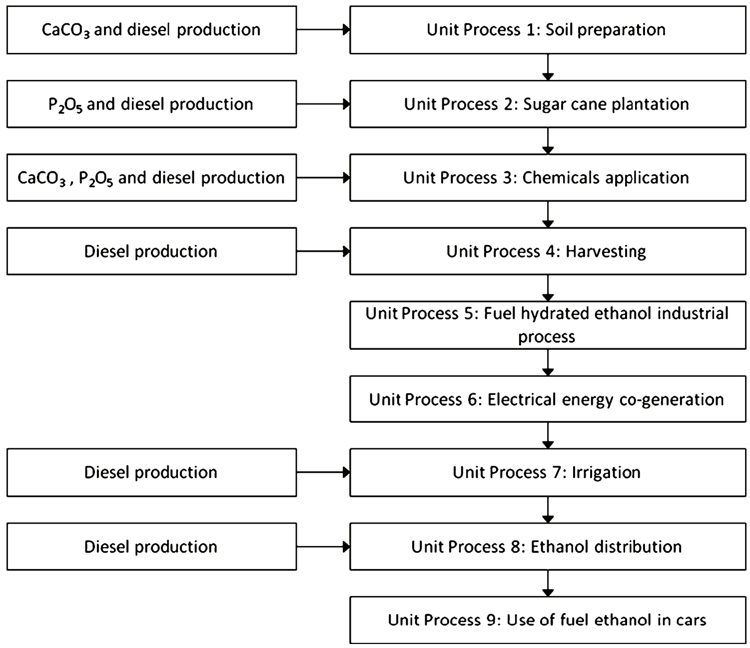


Figure 13. Ethanol Production Process With Fuel Inputs (Ometto et al, 2009).

Inventories of these resources and inputs were calculated for each unit process, with water lifecycle data from the SimaPro database based on indirect water usage from other resources such as calcium carbonate and diesel or obtained directly from cataloguing direct inputs into the ethanol production process. They ultimately traced water usage to that of soil preparation, sugar cane plantation inputs, application of chemicals such as pesticides, direct irrigation, sugarcane harvesting, fuel-hydrated ethanol processing involving sugarcane washing and juice extraction, electricity cogeneration from generators driven by any extracted steam from the sugarcane, and ethanol distribution. These values for water usage are summarized below in **Figure 14**, where they point out that the largest amounts of water usage can be traced to water required for the ethanol processing and for electricity generation. Given the large amounts of resource inputs for ethanol production, the authors suggest that water-recycling systems be implemented and that sugarcane washing be eliminated, in addition to transitioning from diesel to renewable fuels in terms of reducing emissions (Ometto et al, 2009).

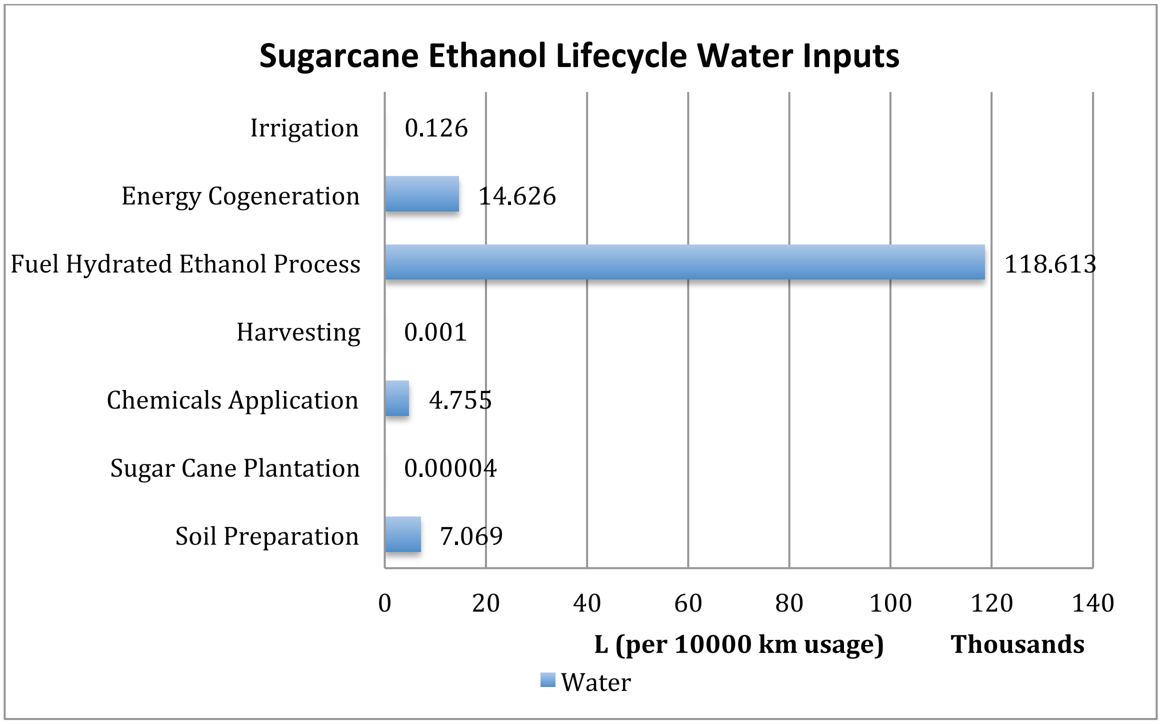


Figure 14. Water Inputs for Ethanol Production Lifecycle (Ometto et al, 2009).

That said, while the above lifecycle inventory provides some insight into water inputs across the entire ethanol production process, the above study does not distinguish between water withdrawn and water consumed, and that sugarcane ethanol is not as viable as corn and cellulosic ethanol in the United States. Such water input inventories have particularly been conducted on corn ethanol, which forms the majority of ethanol sold and consumed in the United States used either as a gasoline additive or in the form of a ethanol-petroleum blend (E85). Aden (2007) performed a life cycle assessment of water usage for current and project ethanol production for current corn-based fuels and in-development thermochemical and cellulosic ethanol processing, with a focus on crop production and fuel processing. Aden points out that the water usage in crop production varies greatly based on local and regional conditions, and he points out that 96 percent of corn irrigation is not irrigated at all; for the crops that are irrigated, he estimates based on USDA data that up to 785 gallons of water are used for each gallon of ethanol produced (Aden, 2007). In terms of corn ethanol production, the author accounts for both wet milling and dry grinding processes where water is recycled within the production facilities, with water usage primarily in energy production (as in Ometto et al (2009)) and between 3 to 4 gallons per produced gallon of ethanol.

Aden (2007) also expanded his inventory assessment to cellulosic ethanol production, which at the time of publication was a prototype process where biomass such as corn stover, wheat, switchgrass, or wood waste is processed biochemically using sugars fermentation or thermo-chemically via low pressure gasification. Production water demands, which are illustrated in **Table 11**, are based on a non-optimized biochemical process as well as on a thermochemical process design that minimizes water by using air-cooling methods. Ultimately, Aden points out that since water demands are closely tied with energy consumption one method in reducing water inputs in ethanol production would be to reduce energy consumption and to produce more concentrated ethanol, as well as to reduce water demands in fuel processing by replacing water-cooling processes with air cooling.

Table 11. Ethanol Production Water Demands by Technology (Aden, 2007).

Freshwater Demands	Percentage of plants using cooling towers	Percentage of plants using boilers	Total Water Demand (water-ethanol ratio)
(Baseline) **Corn Ethanol (Dry Grinding)**	68	32	3-4
Cellulosic Ethanol, Biochemical (Non-optimized)	71	29	6
Cellulosic Ethanol, Thermochemical (Minimized)	71	29	1.9

Harto et al (2010) provides a consumption-based water outlook for life cycle inputs for a series of biofuels and other low-carbon alternative transportation fuels, of which corn and cellulosic ethanol are two fuels considered. The authors calculated life cycle water inputs for ethanol from processes including crop production, farm inputs, processing plant construction, fuel production, and fuel distribution based on several data sources (such as using the Economic Input-Output Life Cycle Analysis (EIOLCA) database for facilities construction) and several assumptions (for example, they assume that ethanol distribution pathways would be the same as that of petroleum gasoline). For cellulosic ethanol, the authors consider mainly switchgrass ethanol in cases where the feedstock is not irrigated and where the feedstock is grown in drought conditions due to the fact that no statistics are available for a distribution of irrigated and non-irrigated feedstock production; for plant construction, the authors used equivalent values for that of corn ethanol since cellulosic ethanol production is still in development. From these calculations, the authors determined a range of water consumption values (as well as weighted averages) for each process and fuel type, with significant amounts of water consumption in crop irrigation, particularly in drought conditions for cellulosic feedstock (Harto et al, 2010).

Other studies have focused more on regional variations in water consumption for corn and cellulosic ethanol production. Wu et al (2009) catalogued water consumption for ethanol crop irrigation and fuel production for both fuel types across three dominant corn regions in the United States using the water inputs structure summarized in **Figure 15**. The regions assessed included the upper and lower Midwest where 95 percent of corn ethanol production is based, with the assumptions that corn crops are irrigated or non-irrigated and cellulosic biomass is non-irrigated.

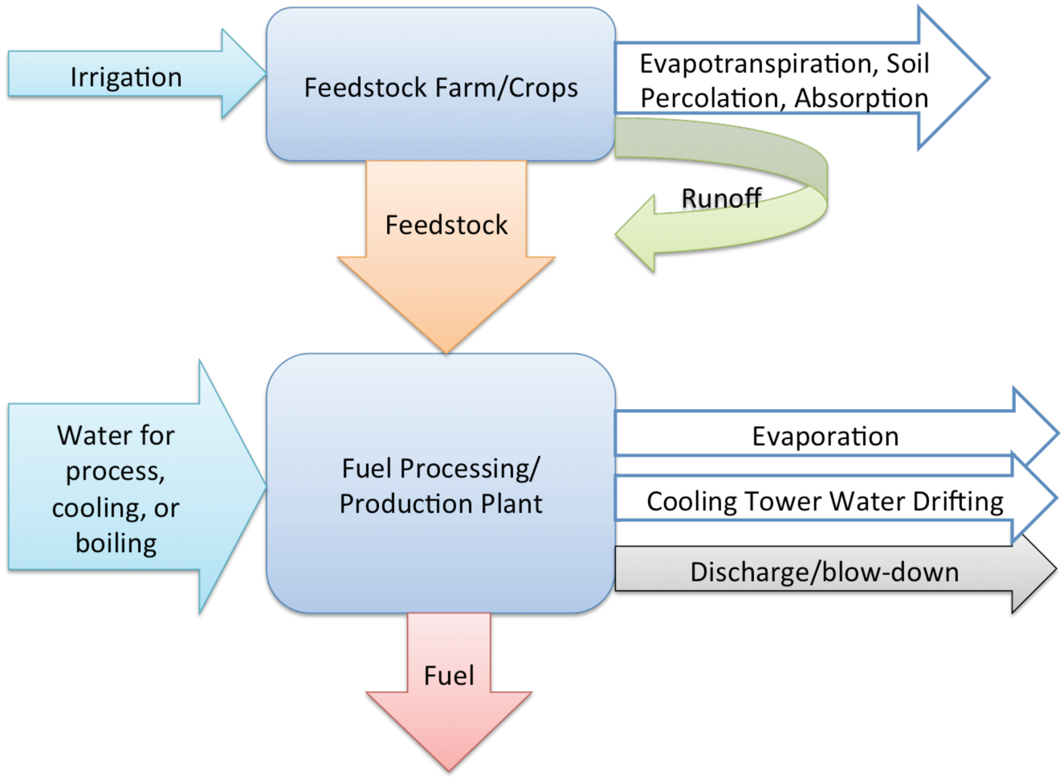


Figure 15. Water Inputs and Outputs for Ethanol Production (Adapted from Wu et al, 2009).

In general, the researchers observed that the majority of water consumption for corn ethanol is in corn production itself for USDA Regions 5, 6, and 7, with Region 7 (situated in the upper Midwest region of the United States) requiring as much as 129 liters of water for each kilogram of corn due to irrigation while the other two regions require little to no irrigation. Despite the large disparity in water consumption, the authors point out that Region 7 produces only 20% of corn in the United States while the other two regions account for 68% of total corn production. For corn ethanol production, Wu et al (2009) note that water is required in the grinding, liquefaction, fermentation, separating, and drying processes as either direct process water or cooling water. The authors also examined water consumption for dry milling facilities, where they pointed out a downward trend in water consumption from the 1990s, from which they obtained a production-weighted average (across all regions) to be 3 liters of water consumed per liter of produced ethanol, with the main variations in water consumption being in water inputs for irrigation across all major production regions (**Table 12**).

Table 12. Ethanol Production Water Consumption by Region (Adapted from Wu et al, 2009).

USDA Region (State Abbreviations)	Share of Ethanol Production, %	Share of Corn Production, %	Irrigation Water Consumption, gal/gal Fuel	Ethanol Production Water, gal/gal Fuel	Total Consumed Water, gal/gal Fuel
Region 5 (IA, IN, IL, OH, MO)	51	53	7.1		**10.1**
Region 6 (MN, WI, MI)	17	17	13.8	3 (Weighted Average)	**16.8**
Region 7 (ND, SD, NE, KS)	27	19	320.7		**323.7**

In terms of cellulosic ethanol, the authors found that most feedstock crops such as switchgrass and wheat required minimal amounts of water consumption for irrigation, while forest wood and wood waste required no irrigation at all; that said, they noted that cellulosic ethanol production, as Aden (2007) stressed, was still in a developmental phase. In terms of projected cellulosic ethanol production, they found varying water demands depending on the technology used as well as the extent of water recycling based on previous studies; these water consumption figures, along with water consumption for corn ethanol by region, are summarized below in **Figure 16**.

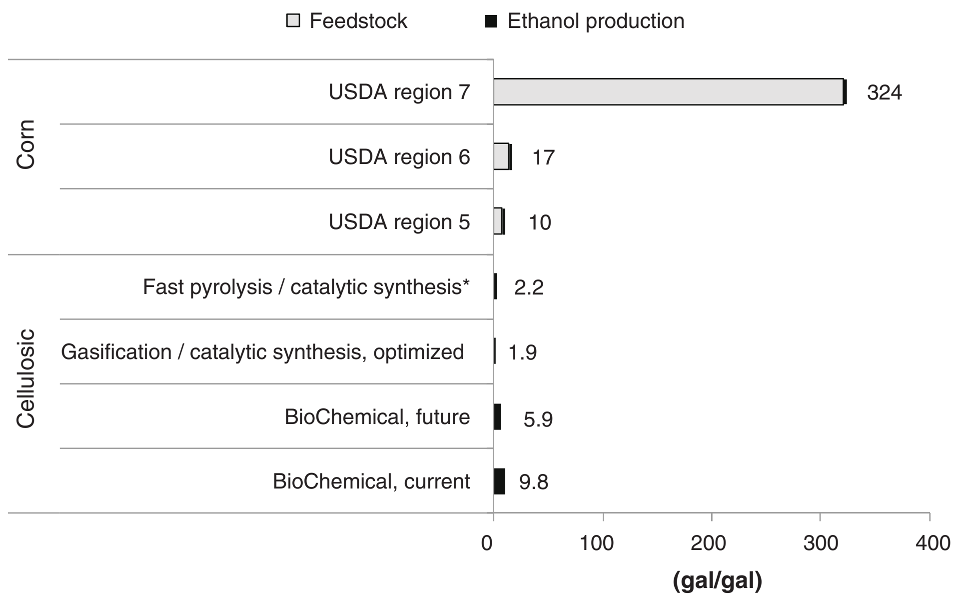


Figure 16. Comparison of water consumption for corn versus cellulosic ethanol (by region and technology) (Wu et al, 2009).

3.4.3. Water Consumption for Biodiesel

Another fuel of interest is biodiesel, in which the United States is the world's largest soy exporter and that soybean crops are well established and feasible for large-scale fuel production (Harto et al, 2010). Biodiesel is a fuel consisting of monoalkyl esters based off of animal or plant oil and is produced via a reaction of triclycerides and methanol or ethanol with a mixture of alkali, acids, or enzymes (Li et al, 2008). While biodiesel can be produced from a wide variety of base feedstock of which producers can extract alkyd esters for biofuel production, the vast majority of biodiesel is produced from soybean or canola oil while other available feedstock are considered too limited for widespread production. That said, additional research into biofuels has resulted in other potential biodiesel production feedstock such as for algae-based biodiesel. In addition to an assessment of water consumption for ethanol fuels, Harto et al (2010) also examines water consumption factors in the life cycles of soybean and algae-derived biodiesel with a similar delineation of sub-processes where water consumption is notable. As with ethanol, the authors divided water consumption into farm inputs and irrigation for soybean feedstock, along with biodiesel production and associated facility construction, as well as to fuel distribution. While water consumption overall is notably lower than that of corn ethanol production, soy biodiesel production still consumes significantly more water in its production lifecycle compared to that of conventional fossil fuels for transportation use.

Soybean-derived biodiesel is also one of the two fuels comprehensively assessed in Sheehan et al (1998) where the authors focused on life cycle resource flows and emissions for a public transport bus. In their analysis, they broke down biodiesel production into several sub-processes, just as with the assessment in Harto et al (2010): soybean agriculture, intermediate transport to processing facilities, soybean crushing, soybean oil conversion, and fuel distribution. For agriculture, the authors examined all resource inputs such as fertilizers and agrochemicals, water use in terms of irrigation, as well as water required for energy inputs and agrochemicals production. For intermediate transport, the authors considered freight truck transport of soybean feedstock from agricultural regions to nearby soybean crushers and oil processing facilities. For soybean crushing and oil extraction, the authors considered a typical process chain as shown in **Figure 17** where steam is a key resource input in soybean meal processing, oil recovery, and wastewater treatment (Sheehan et al, 1998). Total water usage for soybean crushing and extraction was based on electricity consumption, steam production, natural gas usage, and hexane material inputs into the crushing process.

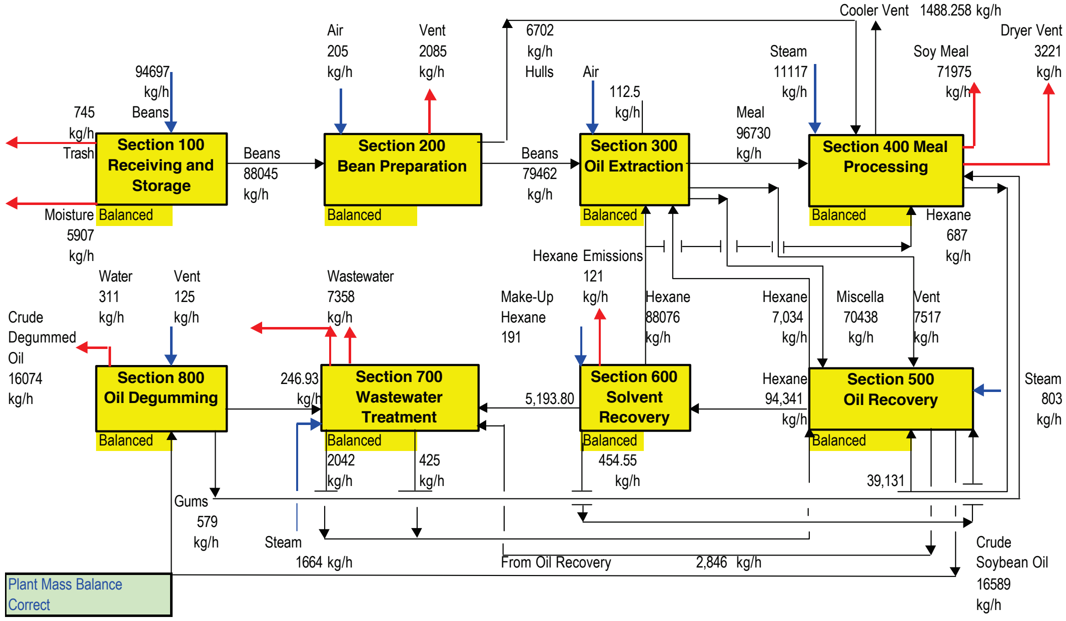


Figure 17. Process Flows for Soybean Crushing/Oil Extraction (Sheehan et al, 1998).

For biodiesel conversion, the authors considered conversion facilities located in urban areas as they note that urban facilities can also process other biodiesel oil inputs such as recycled grease and used vegetable oil. Assuming freight train transportation of soybean oil to these facilities, the authors examined process flows for intermediate transportation and soybean oil conversion, where water is used in railcar loading, (indirectly) in rail transportation inputs, and in crude oil refining (primarily as wash-water for the soybean oil and esters) and methyl ester purification as shown in **Figure 18**; water inputs were allocated for steam production, electricity consumption (based on a national average), direct process water, and water used to produce methanol, sodium methoxide, sodium hydroxide, and hydrogen chloride. For biodiesel transportation, the authors considered truck-based fuel distribution and calculated water inputs in terms of truck loading and transportation inputs.

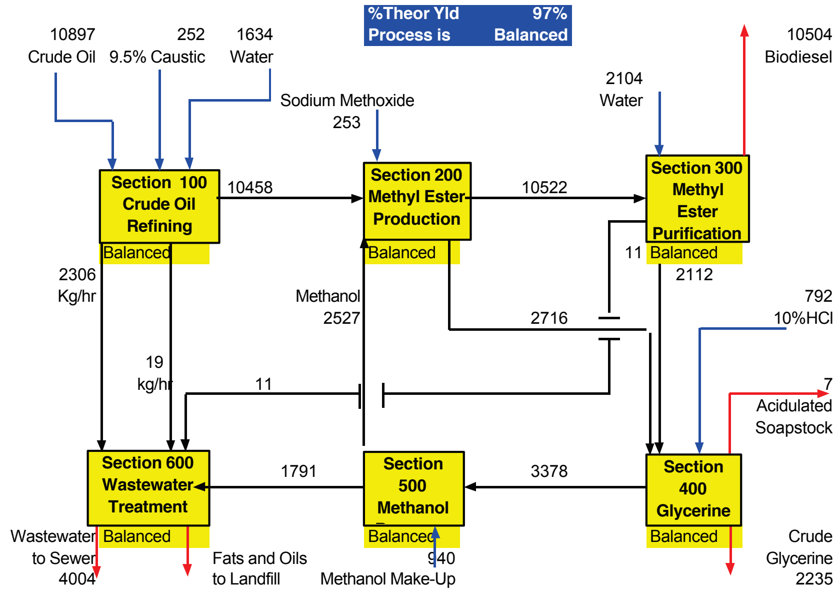


Figure 18. Process Flows for Soybean Oil Conversion (Sheehan et al, 1998).

A summary of overall water usage in biodiesel production and transport determined by Sheehan et al (1998) is shown below in **Figure 19.** It should be noted that the authors do not distinguish between water consumption and withdrawal, and that the resource input allocations were determined based on national averages and assumptions regarding projected biodiesel production pathways; as such, the water inputs in this life cycle assessment may not necessarily reflect conditions in all regions across the U.S.. That said, the overall trend in water usage for Sheehan et al (1998)'s biodiesel life cycle assessment supports the water consumption trends witnessed in Harto et al (2010) and other associated sources, where agricultural water consumption constitutes the vast majority of life cycle water inputs for soybean-based biodiesel as well as for ethanol made from irrigated feedstock.

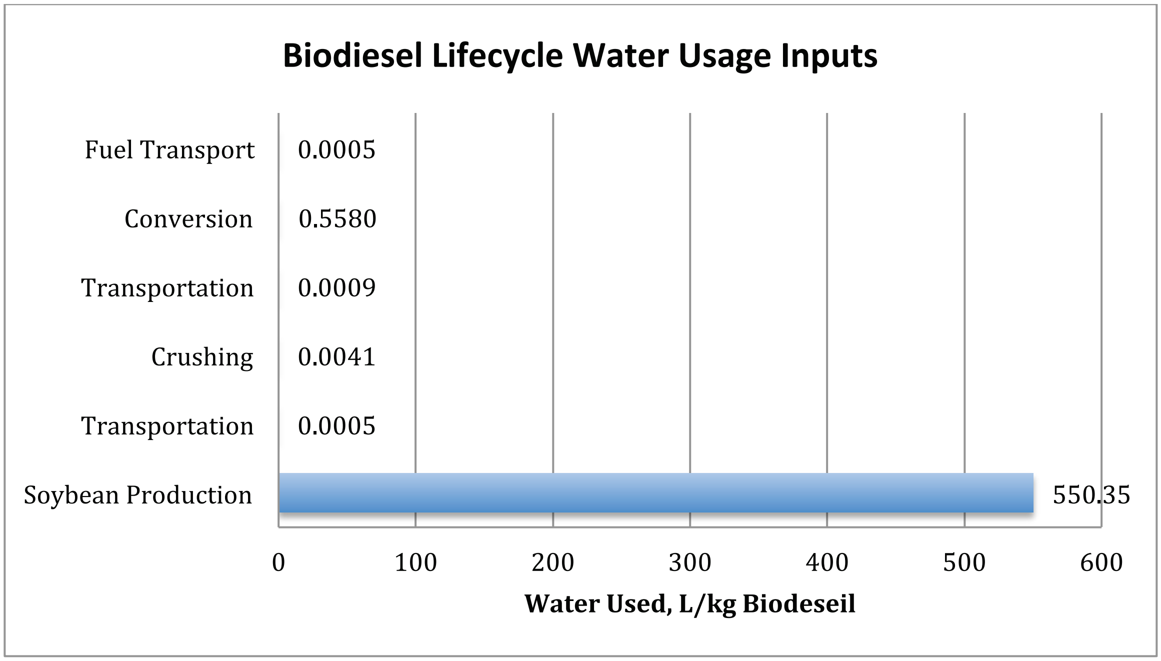


Figure 19. Summary of Water Used in Biodiesel Production Lifecycle (Adapted from Sheehan et al, 1998).

In addition to soybean-derived biodiesel, the authors also examine microorganism-derived biodiesel, in which the microalgae feedstock for this and associated fuels grow more rapidly than that of conventional feedstock such as that of switchgrass and soybeans and have a 10 to 20 percent greater photosynthetic efficiency, meaning that microalgae-derived biodiesel requires significantly less land for feedstock production and that the fast-growing microorganisms can foster resilient biodiesel reserves and increased demand for this and associated biofuels. That said, Harto et al (2010) and Chisti (2007) point out that microalgae-derived biodiesel has some significant economic barriers as current capital costs are significantly higher than that of other fuel production processes, even with widespread adoption of microalgae biodiesel (Harto et al, 2010; Chisti, 2007; Li et al, 2008).

In terms of water consumption, Harto et al (2010) examined two production configurations, one with enclosed, tubular photobioreactors, and one with open ponds.

The authors point out that water consumption for enclosed biodiesel production can potentially be significantly less than that of open biodiesel production and that enclosed systems allow higher yields and better process control (albeit at a higher cost) (Harto et al, 2010).

3.4.4. Discussion

As with thermoelectric fuels and electricity generation, water is an essential input for transportation fuel production and distribution with water consumed in the extraction or harvesting of raw materials or feedstock, the processing of these materials into conventional or alternative fuels, and the distribution of these fuels.

Of note in these assessments is that biofuels consistently have higher water consumption values in the extraction and processing of fuels, with the highest amounts of water consumption as described in these assessments stemming from evapotranspiration due to the intensive irrigation of biofuels; similarly, some additional recovery technologies in the extraction of petroleum require significant amounts of water, although more conventional recovery technologies use less water. It should be noted that these water consumption values for fuel or feedstock extraction vary greatly across different regions due to differing environmental conditions, as with electricity generation water consumption in various regions across the United States.

The fuel production water consumption values compiled from these assessments are summarized below in **Tables 13** to **15** for petroleum and synthetic fuel production for gasoline and diesel, **Table 16** for ethanol production, and **Table 17** for biodiesel production.

Table 13. Summary of Water Consumption Values for U.S. Onshore Petroleum Production.

Process	Sub-Process	Technology	Water Consumed (low), l/l	Water Consumed (high), l/l	Average Water Consumed, l/l	Reference
Exploration					0.000348	Gleick, 1994
Extraction	Primary Recovery		0.1044	0.2784	0.21	
	Secondary Recovery	Water Flooding			20.88	
			Note: Based on 80 secondary oil wells		8.6	Wu et al, 2009
		CO2			24.7	Gleick, 1994
			Note: Based on survey of 14 oil companies		13	Wu et al, 2009
		Shell CO2 Project, Denver			4.3	
	Enhanced Oil Recovery	Average			4.176	Gleick, 1994
		Thermal injection	3.48	6.264		
		Air Injection			1.74	
		Micellar Polymer			309.72	
		Caustic Injection			3.48	
		Average for CO2, Steam, Combustion			8.7	Wu et al, 2009
		Weighted Average	Note: Based on technology shares in U.S. for 2008		8	
		Produced Water	Note: 71% of Produced Water is Reinjected		-6.8	
		Net Water Consumed	Subtract (0.71*Produced Water) from Weighted Avg		3.2	
Refining		Traditional	1	2.5		Gleick, 1994
		Reforming	2.088	4.176		
	Aggregate		1	1.85	1.53	Wu et al, 2009
	Survey Range		0.5	2.5		
Transport	Aggregate		0.65	2.7	1.3	Harto et al, 2010
Extraction			2.1	5.4		Wu et al, 2009
Total	Petroleum		3.6	7		
	Gasoline-only		3.4	6.6		

Table 14. Summary of Water Consumption Values for Saudi-Based Petroleum Extraction.

Source Type	Process	Sub-Process	Tech-nology	Water Consumed (low), l/l	Water Consumed (high), l/l	Average Water Consumed, l/l	Ref-erence
Saudi Crude, Ghawar Oil Field	Ex-traction			n/a	n/a	1.4	Wu et al, 2009
Saudi Crude, North 'Ain Dar Field		Enhanced Oil Recovery	Water Flood-ing	n/a	n/a	4.6	
Saudi Average		Aggregate		1.4	4.6	n/a	
	Total			2.8	5.8	n/a	

Table 15. Summary of Water Consumption Values for Canadian Oil Sands Extraction.

Source Type	Process	Sub-Process	Water Consumed (low), l/l	Water Consumed (high), l/l	Average Water Consumed, l/l	Reference
Canadian Oil Sands	In-Situ Oil Shale Extraction		n/a	n/a	≤ 1	Wu et al, 2009
	In-Situ Shale Retorting		1.044	2.088		Gleick, 1994
	Tar Sands Extraction		2.44	6.26		
	Extraction	Surface Mining	n/a	n/a	4.8	
			Note: 2005 Average		4	Wu et al, 2009

Table 16. Summary of Water Consumption Values for Corn and Cellulosic Ethanol Production (Various Sources).

Fuel	Source Type	Process	Technology	Water Consumed (low), l/l	Water Consumed (high), l/l	Average Water Consumed, l/l	Reference
Corn Ethanol	USDA Region 5	Irrigation				7.1	Wu et al, 2009
	USDA Region 6					13.6	
	USDA Region 7					320.7	
	U.S. Avg., Irrigated			25	403	128	Harto et al, 2010
		Farm Inputs		2.1	6.5	4.1	
						0.11	King and Webber, 2008 (1)
		Production	Old Dry Mill			5.8	Wu et al, 2009
			Dry Mill Average	Note: As of 2005		3	
			Minnesota Dry Mills	4	4.2		
			Aggregate	1	11	4.7	Harto et al, 2010
			Dry Milling Average, MN	3.5	6		King and Webber, 2008 (1)
		Distribution	Same as gasoline	0.65	2.7	1.3	Harto et al, 2010
Cellulosic Ethanol	U.S. Avg., Non-irrigated	Irrigation	Aggregate	0	0	0	
		Farm Inputs		0.92	3.4	1.8	
	U.S. Average, Drought	Irrigation		352	411	382	
	U.S. Average, Switchgrass	Production	BC process/ Gasification			9.8	Phillips et al, 2007
			Thermochemical			1.9	Aden , 2007
			Forest Residue Pyrolysis			2.3	Wu et al, 2009
			Stover Production			7.3	King and Webber, 2008 (1)

Table 17. Summary of Water Consumption Values for Soybean and Microalgae Biodiesel Production (Various Sources).

Fuel	Process	Source	Water Con-sumed (low), l/l	Water Con-sumed (high), l/l	Average Water Con-sumed, l/l	Ref-erence
Soybean Biodiesel	Irrigation		11	286	120	Harto et al, 2010
	Farm Inputs		1.2	30	11	
	Production		1	1	1	Merson et al, 2006
	Distribution	Same as gasoline	0.65	2.7	1.3	Harto et al, 2010
Micro-algae Biodiesel	Extraction Process Water	Closed Tube	28	57	40	
		Racing Pond Surface Evaporation	0	575	165	
		Racing Pond Process Water	31	80	50	

However, it should be noted that these water consumption values represent the amount of water that is removed or evaporated from the local environment and not returned in some form from these fuel production processes. In actuality, total water usage, which includes withdrawing and returning some amount of water to local reservoirs or ecosystems, is much higher than these values. Available water withdrawal *and* consumption statistics for these fuels are summarized below, including an inventory of water usage inputs for diesel and biodiesel production sourced from Sheehan et al (1998) as well as water usage inputs for sugarcane ethanol from Ometto et al (2009) and corn ethanol water usage from King and Webber (2008, 2) and other sources. While these values are not directly applicable to this thesis as this assessment is focused on water consumption from these fuels, the below values for total water usage emphasize even more the interconnections between water and fuel production. Water usage for transportation fuel production is summarized below in **Tables 18 to 21.**

Table 18. Summary of Water Used in Diesel Production (Sheehan et al, 1998).

Source Type	Process	Sub-Process	Technology	Water Used, l/kg	Water Used, l/l	Total, l/l fuel	Referenc e
U.S. Crude	Extract-ion	Onshore	Con-ventional	0.0003	2.50E-04	0.184	Sheehan et al, 1998
		EOR	CO_2/Steam	0.221	1.84E-01		
	Refining	Fuel Inputs	Coal Input	5.80E-08	4.83E-08	8.04E-04	
			Diesel Input	6.15E-05	5.12E-05		
			Heavy Fuel Input	3.26E-04	2.71E-04		
			Natural Gas	6.33E-09	5.27E-09		
			Petroleum Coke	0.000135	1.12E-04		
			Propane	5.13E-10	4.27E-10		
			Steam	3.92E-10	3.26E-10		
			Electricity Input, U.S.	4.44E-04	3.69E-04		
			Cracking Catalyst	2.77E-07	2.30E-07		
			Other	3.39E-09	2.82E-09		
	Trans-port	Crude to Refinery	Aggregate	3.92E094	0.00033	0.0007 8	
		Fuel to Storage		5.41E-04	0.00045		
Foreign Crude	Extract-ion	Onshore	Con-ventional	3.3E-04	2.7E-04	0.0505 1	
		EOR	CO_2/Steam	0.0604	0.05024		
	Refining		Direct Water	0.0145	0.0107	n/a	Sutter et al, 2007
U.S. Crude	Extract-ion	Not specified			0.42	12.92	King and Webber, 2008 (1)
	Refining				12.5		

Table 19. Summary of Water Used in Soybean Biodiesel Production (Sheehan et al, 1998).

Process	Sub-Process	Technology	Water Used, l/kg	Water Used, l/l	Total, l/l fuel	Reference
Extraction	Agri-culture	Irrigation	550.329	484.29	485.45	Sheehan et al, 1998
		Fertilizer	0.0131	0.01		
		Agrochemicals	0.00521	0.00		
	Farm Inputs	Natural Gas	5.03E-13	0.00		
		Diesel	0.00519	0.00		
		U.S. Electricity	4.04E-05	0.00		
	Harvesting	Diesel	1.29	1.14		

Table 19 (continued).

Process	Sub-Process	Technology	Water Used, l/kg	Water Used, l/l	Total, l/l fuel	Reference
Processing	Crushing	NG Usage	6.74E-09	0.00	0.0031	Sheehan et al, 1998
		Steam Production	6.96E-09	0.00		
		Hexane Inputs (from Production)	0	0		
		Direct Process Water	0.00353	0.00		
	Con-version	Steam Production	7.99E-09	0.00	0.49	
		Electricity Consumption	0.000182	0.00		
		Methanol	0.147549	0.13		
		Sodium Methoxide	0.101	0.09		
		Sodium Hydroxide	0.00996	0.01		
		Hydrogen Chloride	0.00638	0.01		
		Direct Process Water	0.293	0.26		

Table 20. Summary of Water Used in Sugarcane Ethanol Production in Brazil (Ometto et al, 2009).

Source Type	Process	Technology	Remarks	Water Used kg/10000 km	Reference
Brazil. Sugarcane	Soil Preparation	Diesel and Calcium Carbonate	Note: Water from Diesel and CaCO3	7069.11	Ometto et al, 2009
	Plantation Inputs	Diesel	Note: Water from Diesel	0.044	
		Chemicals	Note: Water from Diesel, P2O5 and CaCO3	4755.33	
	Harvesting	Diesel	Note: Water from Diesel	1.29	
	Processing	Fuel-Hydrated Ethanol Process Note: Direct Inputs		118613	
		Electricity Cogeneration	Note: Direct Inputs	14625.27	

Table 21. Summary of Water Used in Corn and Switchgrass Ethanol in the U.S. (Various Sources).

Fuel	Source Type	Process	Water Used, l/l fuel	Reference
Corn Ethanol	Grain, Pennsylvania	Irrigation	180	King and Webber, 2008 (2)
	Grain, U.S. Avg		780	
	Grain, Arizona		2100	
	Grain, U.S. Avg	Processing	3	
Stover/Switchgrass Ethanol	Switchgrass, PA	Irrigation	170	
	Switchgrass, U.S.		760	
	Switchgrass, AZ		2100	
	Switch, U.S. Avg	Processing	7.3	
Corn/Switch Mix	50-50 Mix, PA	Irrigation	81	
	50-50 Mix, U.S.		350	
	50-50 Mix, AZ		960	
Corn Ethanol	Average	Farming	248	Chiu et al, 2009; Pimentel and Patzek, 2005
		Processing	40	
	Georgia	Farming	94	Chiu et al, 2009
		Processing	2.5	

3.5. Indirect Water Consumption From Tank-to-Wheel Fuel Consumption of Passenger Vehicles

While the above studies and assessments of conventional fuels, biofuels, and energy generation in terms of water consumption and usage have been conducted from a well-to-tank (WTT) approach where the above fuels are extracted and processed/produced, we need to determine how much of those fuels are actually consumed within a mobility network from a tank-to-wheel (TTW) perspective. When considering TTW water consumption, three areas of vehicle operation are considered: water consumed in the production of these fuels (from which the vehicle gradually consumes these fuels over some driving distance or time), water directly inputted into the vehicle as a coolant or required to produce any necessary operational fluids (such as engine lubricant, antifreeze, and hydraulic fluids) where these fluids are regularly replaced or gradually consumed, and water required for servicing and maintaining these vehicles.

The most dominant component of water consumption in tank-to-wheel vehicle operation within a mobility network would be tank-to-wheel fuel consumption within the vehicle itself, where the general metric measuring fuel consumption (and ultimately indirect water consumption) would be the vehicle's fuel efficiency over the number of vehicle miles traveled (VMT). Two such studies focused on water consumption for each vehicle mile traveled were conducted by Carey King and Michael Webber, in which they focused on water usage in light-duty vehicles of differing fuel sources based on normal driving conditions and vehicle fuel efficiencies. The first study examined the water consumption stemming from the usage of plug-in vehicles, particularly batter-electric vehicles or plug-in hybrids by conducting an initial analysis on how transferring from conventional gasoline to electric propulsion systems would impact water resources (King and Webber, 2008 (1 & 2)).

To do this, they used annual gasoline consumption and mileage statistics for light-duty vehicle fleets. For PHEVs, the researchers use existing data on PHEV research, such as vehicle specific energy outputs and electric system efficiencies, as well as data on gasoline distribution and water usage, to determine the number of PHEVs (and ultimately the number of PHEVs) needed to displace a target amount of gasoline. Based on PHEVs with a 40-mile electric range, they found that these vehicles needed to displace 860 million miles total over 44.1 million PHEVs. In terms of water consumption, they used data previously collected from other studies and surveys to find that 0.42 gallons of water were used to extract one gallon of gasoline in the U.S.; this value serves as a benchmark against the inclusion and transplantation of PHEVs and BEVs. They also examined the water consumption for the mining and processing of electricity generation fuels, particularly on the mining of coal, uranium, and natural gas, along with the water consumption for electricity generation. Combined with the previous driving statistics, they estimate that 0.09 gallons of water per mile and 0.23 gallons per mile would be consumed based on extraction and thermoelectric cooling, respectively. Based on those results, they also find that based on the same driving distance electric vehicle systems would use 17 times more than that of gasoline vehicle systems. The authors find that attempting to replace the conventional vehicle subset with PHEVs would take seven years to complete with a threefold increase in water consumption and 17-fold in water withdrawal, noting that for the transplant of PHEVs to be sustainable, more research for renewable electricity sources and more effective regional water plans would need to be implemented.

A later study builds upon the water usage findings for PHEVs and BEVs by expanding the water usage investigation to natural gas, biofuels, diesel, hydrogen from natural gas or electrolysis, and petroleum from oil shale and tar sands; the water intensity calculated for each fuel was compared to corresponding fuel efficiencies to determine the amount of water used per driven mile for each type of vehicle. Overall, King and Webber found that fuels that were directly derived from fossil fuels consumed more water than their alternatives (fuel indirectly stemming from fossil fuels or biomass) with the least water used coming from petroleum fuels, natural gas-derived hydrogen, renewable electricity sources, and non-irrigated biofuels. LDVs running on electricity from thermoelectric generation - which uses significant amounts of water cooling - consumed

2-5 times more water and used 5-20 times more water, while vehicles using irrigated biofuels used 1-3 times more water than those using petroleum fuels (King and Webber, 2008 (1)). To indicate which factors within the procurement of these fuels yielded the most water usage, the authors conducted a sensitivity analysis that indicated fuel economy and irrigation as the main driving factors for water intensity. That said, they also noted that the analysis was potentially too simplified because of using national averages; a regional analysis of water intensity would be more helpful in implementing alternative fuels successfully.

As part of their life cycle water consumption assessment on ethanol and biodiesel fuels along with low-carbon electricity generation (along with their associated feedstock), Harto et al (2010) considered a comparison of tank-to-wheel water consumption for each vehicle type stemming from fuel consumption. Assuming that the implementation of low-carbon fuels would coincide with improved vehicle efficiencies, the authors considered unleaded gasoline and biofuel consumption within a Toyota Prius (with a combined efficiency of 46 miles per gallon), while for plug-in hybrid vehicles and electric vehicles they also considered energy consumption in the Chevrolet Volt and Tesla Roadster (0.18 kWh per mile and 0.2 kWh per mile, respectively), where biofuel efficiencies were adjusted based on biofuel-gasoline consumption ratios provided by the Environmental Protection Agency. For electric vehicles, the authors considered homogeneous energy generation scenarios where either coal and carbon sequestration, photovoltaic solar (PV), and concentrated solar power (CSP) was considered as the primary energy source. The water consumption estimates from fuel consumption were also included with water consumption traced from the manufacturing of these vehicles, where they found that in general ethanol and biodiesel fuels – for both irrigated and non-irrigated feedstock conditions – consumed notably more water than their electric and gasoline counterparts; that said, the authors noted that including manufacturing water consumption into the assessment showed that electric vehicles consumed more water in manufacture than their conventional counterparts (the authors assumed that biofuel and gasoline vehicles were equivalent in terms of manufacturing), which converged the water consumption results somewhat (Harto et al, 2010; **Table 22**).

Table 22. Tank-To-Wheel Water Consumption from Fuel Consumed Per Type (Adapted from Harto et al, 2010).

Fuel Type	Low Value (gallons per VMT)	High Value (gallons per VMT)	Average Water Consumed (gallons per VMT)
Unleaded Gasoline	0.04	0.13	0.07
Coal and Carbon Sequestration	0.13	0.35	0.21
PV Solar	0.016	0.044	0.027
CSP Solar	0.2	0.26	0.23
Corn Ethanol	0.84	13	4.1
Switchgrass Ethanol, no irrigation	0.1	0.37	0.19
Switchgrass Ethanol, irrigated	11	13	12
Soybean Biodiesel	0.23	5.3	2.2
Algae Biodiesel – Closed Tubes	0.53	10.9	3.6
Algae Biodiesel – Open Ponds	0.5	1.04	0.72

Other studies have also investigated how the type of road and corresponding vehicle behavior (traffic and congestion) can affect the amount of material inputs for various forms of transportation. Saari et al (2007) use the material input per service unit (MIPS) concept (the total amount of materials or resources used for a product over a specific time or distance period) to determine the natural resources consumption across vehicle types and road types in Finland. While other studies on environmental impacts from road transport focus on emissions and other effluents, the researchers investigate the material and energy consumption of road systems and vehicles across their life cycles. Vehicle types considered included cars, buses, bicycles, trucks, and commercial vehicles with life cycles across 60,000 km; road types included connecting roads, regional roads, motorways, and bicycle paths with life cycles covering construction, maintenance, and disposal over 60 years. Material inputs for Finnish roads were calculated based on structural layers such as tunnels, bridges, and intersections as well as on any potential structural improvements or maintenance schemes such as repaving or gritting. For vehicles, the researchers used MIPS values for materials, energy, and water used during production as well as associated values stemming from fuel consumption or parts during normal usage and maintenance; they also included MIPS for materials, energy, and water used in vehicle disposal and recycling (materials or components with no definitive data were omitted from the assessment). The MIPS values, which consist of ratios of lifecycle consumptions of water, energy, and materials over a defined service unit or range, were calculated based either on infrastructure use frequency or vehicle use.

As expected, the researchers found that resource consumption for roads varied with road types, with the greatest resource consumption (including water usage) from car usage on connecting roads (surface streets) due to limited passenger capacity and traffic conditions. Due to traffic volume on major roads such as motorways and main arteries, water consumption did not change significantly (with the exception of connecting roads where usage was up to three times greater than those of larger roads). Based solely on traffic volume for each type of road and material inputs within the road infrastructure, resource inputs for cars were much greater than those of buses, while inputs were very similar when compared against gross weight.

3.6. Overview of Mobility Networks and Transportation Systems

Cities and urban regions primarily exist in order to support organizational structures and operations, as well as to provide “opportunities for human interactions,” especially in past conditions where available transportation and communication technologies constrained essential movement within “concentrated areas of residence, work, and exchange” (Bertolini & Djist, 2003). That said, improvements in transportation as well as changes in socioeconomic factors have allowed for a decoupling of mobility and these cities, resulting in “network environments” and “network cities where “networks of interaction between people, firms, and other organizations superimpose their autonomous, different logic on territorially constrained spatial developments” (Bertolini & Djist, 2003). That said, even with the advancement of virtual communication technologies and increases in urban sprawl due to loosened constraints on physical movement, there is also an increase in dense urban regions that facilitate physical human interactions.

In a nutshell, mobility environments consist of transportation systems, institutions and activity spaces that can “influence…the presence of people in a given location”; notably, it has been suggested that accessibility is a dominant factor in the performance of these environments as this would determine the “likelihood of the presence of particular individuals and groups there” depending on the demands of the served inhabitants (Bertolini & Djist, 2003). A sizable component for analyzing the accessibility of these environments is the mobility network’s transportation system and its related elements, where Litman (2003) builds upon the notion of accessibility by proposing traffic amounts and mobility as two other measures of performance for transportation systems, with traffic pertaining to vehicle movement and mobility pertaining to the movement of objects within these network environments. In particular, Litman defines possible metrics of transportation system performance such as vehicle-miles (VMT) for measuring traffic-related performance, passenger-miles traveled (PVMT), and travel times for measuring accessibility of these systems (as in, how much time is required for traveling to a specific location for a given mode or urban network). However, each measure of effectiveness proposed "affects the perceived value of different modes" where VMT places heavy emphasis on motorized travel and PVMT leaves out shorter-distance mobility, primarily due to how data pertaining to each variable has been collected and presented (this was evidenced in the above water impacts assessments where the main metrics for vehicle modes were VMT and vehicle efficiency). The skewed nature of each of these performance metrics for transportation systems results in different distributions of all applicable transportation modes for a given region (Litman, 2003; **Figure 20**).

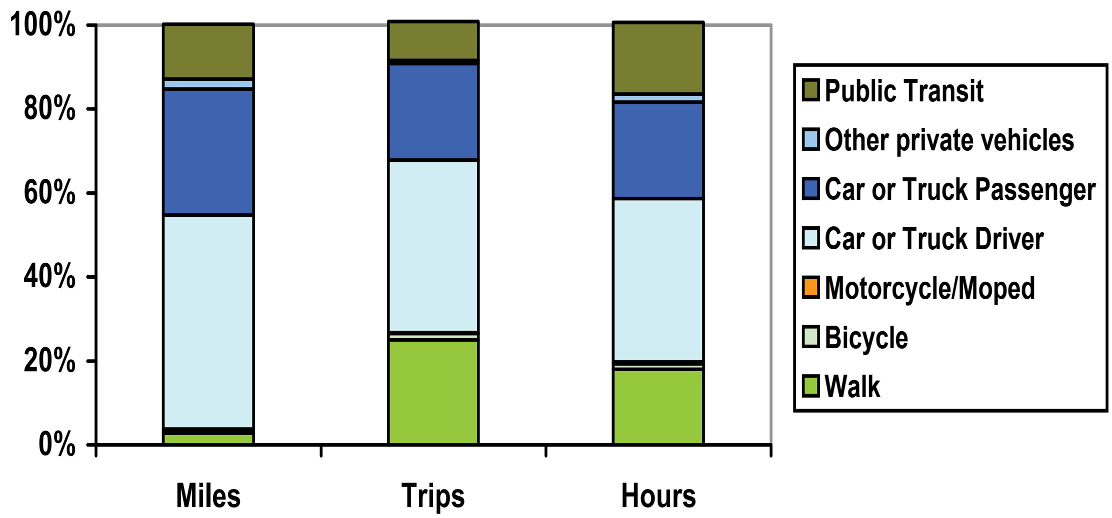


Figure 20. Comparison of Measured Travel Across Measured Miles, Trips, and Travel Time (Litman, 2003).

Increases in urban populations and respective passenger vehicles within these urban regions have placed strains on existing infrastructure and current transportation networks, resulting in increased congestion and reduced transportation system effectiveness. Detrimental cost and environmental impacts traced to increased congestion in U.S. urban regions have been catalogued in the Annual Urban Mobility Report published by the Texas Transportation Institute, where there is a notable increasing trend in wasted fuel costs and travel times in congested cities and metropolitan areas, with an estimated 4.16 billion hours in total traffic delays and an average of 24 gallons wasted per traveler/per year for the United States, with an estimated "congestion cost" in 2007 being $87.2 billion compared to that of $16.7 billion in 1982 (Schrank and Lomax, 2009). Given that an increase in fuel prices will not necessarily reduce congestion, the authors propose a "balanced and diversified approach" by optimizing available service within existing infrastructures, increasing capacity in critical sections of existing mobility networks, and facilitating more transportation choices. That said, there has been some criticism regarding the magnitude of these calculated trends for travel delays and congestion costs; in particular, Cortright (2010) examines the methodology Schrank and Lomax (2009) used in calculating excess fuel consumption costs by "calculating the difference in average fuel economy at free flow speeds and average fuel economy at slower congested speeds" based on a decades-old study based on vehicles traveling along arterial roads. From this methodology, Cortright points out that the calculated fuel economy assumptions are outdated and are not applicable to high-speed situations such as those on highways or restricted-entry road networks (Cortright, 2010). Additionally, this critical review analyzes travel time variations due to urban congestion and finds that the travel time estimates (packaged as Travel Time Indices that are represented as the percentage of time added to that of uncongested conditions) are somewhat inflated. That said, the overall trends in fuel and travel impacts from urban congestion still hold and provide a foundation for further investigation to negative impacts of congested transportation networks.

3.7. Sustainable Transportation: An Overview

The increase in urban populations and expansion of metropolitan areas has also sparked a need to assess environmental impacts for urban transportation and energy systems and to find methods to make transportation within urban regions more sustainable and resilient. As mentioned in the introduction of this thesis, sustainable development has been defined as development of urban regions or economic sectors that can meet current conditions without endangering the needs of future conditions, where Black (1996) mentions that sustainable transportation is defined as a transportation system or sector that meets current needs while not endangering future demands. This is particularly important given that current fuel resources are finite and have detrimental impacts in terms of urban air quality and pollution, in addition to increased congestion in current transportation networks (Black, 1996). In addition to pointing out that petroleum resources are finite and unsustainable, Black also suggests that biofuels would be potentially unsustainable as bioenergy crops would ultimately compete with food crops and that all other alternative forms of petroleum production would only delay the inevitable. Other barriers that Black points out are detrimental environmental impacts of fossil fuels as well as other auxiliary fluids in current vehicles in terms of emissions and material flows as well as excessive land use for current transportation infrastructure.

Based on these areas of concern, the author proposes solutions to increasing the sustainability of transportation systems based on regulating emissions and skewing pricing and technological development towards alternative forms of transportation, along with mitigating the increase in passenger automobile travel. Additionally, Black examines existing sustainability-related policies imposed in the United States and their associated impacts, particularly in labeling fuel economy for passenger vehicles, carpooling and telecommuting, implementing alternative fuel infrastructures, increasing public transit, improved land use management, and taxes on carbon emissions; he notes that all of these policies have helped manage short-term and minor issues but have not helped at all in creating sustainable mobility (Black, 1996). Ultimately, Black suggests that the best way to implement sustainable mobility into the United States and other regions across the world is to focus less on marginal improvements and concentrate on more significant efforts to improve and expand alternative fuel technologies and reconfigure urban areas to increase land use and transportation efficiency.

Similar concerns regarding the effects of policies on sustainable transportation have been echoed by Litman and Burwell (2006), where the authors point out that many environmental, social, and economic issues pertaining to sustainability overlap, meaning that meaningful sustainable transportation policies and analyses need to account for all three types of issues – for example, the authors point out that emissions reduction strategies may "exacerbate other economic, social, and environmental problems" (Litman and Burwell, 2006). Additionally, the authors point out that as opposed to conventional transportation planning where transportation modes are aligned in series from lower-priority walking to high-priority automobile improvements, sustainable transportation planning needs to assume that all modes have equal usefulness. Ultimately, the authors stress that sustainable transportation planning needs to break free of conventional transportation strategies and examine all possible modes and associated indicators or issues.

Just as how sustainable transportation strategies cannot rely on one set of impacts or issues, there is no single remedy for reducing environmental impacts from transportation and energy systems. Lund and Clark II (2007) provide a broad overview of possible changes in increasing the sustainability of transportation and energy sectors, in which they stress that a "synergy of combining necessary technological changes in the transport sector with the better integration of fluctuating renewable energy sources into the electricity supply" is necessary for building a sustainable infrastructure (Lund and Clark II, 2007). The authors examine two existing papers on how alternative vehicles can be implemented into sustainable transportation systems, where it is evident that electric vehicles and other alternative propulsion systems would need to replace existing modes in order to have any significant effects in climate change policies and not just as a secondary vehicle; along with these papers discussing implementing alternative propulsion technologies, the authors look at possible energy system technologies that can support sustainable transportation systems; for example, Lund and Mathiesen (2006) analyzed a 100-percent renewable energy system in Denmark based on 2030 and 2050 projections, based on a development focus on end-user energy savings and the implementation of higher-efficiency energy systems from renewable sources as well as a series of environmental cost assumptions within the EnergyPLAN analysis model, where they find that a fully-renewable energy system is possible with a combination of wind and biomass sources, albeit with reduced energy supplies and uncertainties involving the amount of available biomass reserves in Denmark; on a broader scale, while fully-renewable systems are possible, a combination of technologies and energy-saving measures would be required in order to achieve this (Lund and Mathieson, 2006).

CHAPTER 4

APPROACH AND METHODOLOGY

4.1. Overview

The preceding background and literature review of existing life cycle assessments and studies for water consumption for transportation fuels or energy sources illustrates the vast numbers of variables, amounts of information and data, and individual components that would need to be integrated into a comprehensive model analyzing top-level water consumption for an entire network of multiple transportation modes and infrastructure. Additionally, all of these components would need to be structured and organized in such a way that would facilitate a clear understanding of individual sources of transportation-related water consumption in order to stakeholders to determine any impacts stemming from implementing alternative fuels and transportation modes into said network.

This chapter discusses the approach used to develop a multi-modal transportation system model with the intent of collecting individual life cycle data and assessing network-wide water flows for multiple transportation modes and technologies. The chapter begins with highlighting the overall context of the model as well as laying out the scope of the system to be modeled. From there, several structured engineering processes and principles are examined and assessed, from which we discuss how implementing a structured approach to this transportation system of interest is appropriate. This discussion leads to an examination of object-oriented approaches and a model-based environment via Model-Based Systems Engineering, from where several existing MBSE methodologies are examined. The chapter then provides a brief overview of the Systems

Modeling Language (SysML) and how it can support Model-Based Systems Engineering activities. The application of MBSE is also combined with the implementation of an engineering analysis model in which relevant parametric and quantitative properties can be captured in reusable model elements and quantitative information from the structural components of the system model can be transformed to an analysis context where it can be interpreted by external analysis tools. Based on the above discussion, the chapter then discusses how the engineering analysis model concept can be coupled with MBSE principles and SysML implementation can be used to build a transportation network system model, with the intent of addressing whether water consumption for a multi-modal transportation network can be assessed through a system model developed in SysML.

4.2. Overall Context

The development of a model representing a multi-modal, multi-scale system must account for several factors and issues (Azevedo, 2010). Given the vast amounts of components and factors within a multi-modal transportation system, there needs to be some method to collect information effectively and to represent model elements and factors in a consistent, structural approach (Bras, 2009; Wang, 2008). Based on the research presented in the previous chapter, the most visible issue to address in this model is to integrate the above life cycle data sets and components into a structured model. For example, a model describing water consumption in this network must be able to include inputs from multiple agencies and studies, such as data from regional transit providers or information regarding local road mileage or registered vehicle amounts from transportation agencies. A second component to consider is to develop a model that has enough system detail to allow for spatially explicit conditions. As hinted in the overall research questions for this thesis, a key aspect of this model is to provide a structure that would allow for regional variations, such as for differing electricity generation distributions.

Thus, it is essential for the system model to maintain a consistent approach in combining water consumption components based on information from differing sources and agencies and on pathway scope while it addresses stakeholders' needs in determining the effects on regional water resources from implementing alternative fuels within a multi-modal transportation system. Ultimately, all pertinent factors relating to transportation modes and water consumption need to be effectively allocated and combined systematically in order to develop a network representation and to examine environmental and resource impacts effectively and comprehensively.

4.2.1. System Boundary and Scope of Life Cycle Inputs

Another important issue to address in the development of this model is the system scope for our transportation/mobility network. Since a multi-modal transportation system contains numerous components on differing scales – individual fuels and their production processes, passenger versus public transit vehicles, streets, highways, maintenance and servicing infrastructure, etc. – a system domain boundary is necessary in order to maintain consistency in our model. Since this model also serves as repository for life cycle water consumption data from existing assessments and other models, the scopes for individual pathways such as for transportation and energy fuels and infrastructural components need to be properly defined in order to maintain a direct comparison of water consumption. Consider fossil fuels such as petroleum, for example – while there is direct process water injected into wells in order to extract crude oil through primary or secondary/enhanced recovery methods, there is indirect water consumed from the construction of surrounding infrastructure required for the well as well as water embedded within the crude oil itself (this "produced water" is mainly re-injected into these wells for additional recovery). The same can be said for renewable energy sources and fuel pathways, where in addition to water consumed for irrigation purposes or for direct operation there is also water consumed indirectly from the construction of processing facilities for biofuels or water consumed during the manufacturing of solar panels or other energy plant facilities (Harto et al, 2010).

Although this model will consider life-cycle water flows for transportation and energy fuels as well as for sustaining network infrastructure and vehicle modes, it is not intended to be a full-fledged life cycle assessment – rather, the model will serve as a representation of a portion of the lifecycle for these fuels. The Environmental Protection Agency (EPA) breaks down the stages of a product or system life cycle into *raw materials acquisition, manufacturing, use/reuse/management,* and *recycle/waste management* within a bounded system from which inputs such as raw materials and energy as well as outputs ranging from waste flows to emissions can be examined (Curran, 2006; ISO, 2006; **Figure 21**). As the focus of this thesis is to determine how much water is potentially consumed within a multi-modal transportation network, we are interested primarily in material and energy inputs within the system of interest – whether they be the fuels and raw materials required to maintain and operate a transportation network or direct water inputs themselves – and how these materials are *used or consumed* within the system – in other words, the top-level system boundary is constrained to the use of material and energy inputs. While water consumed in *vehicle manufacturing or initial infrastructure construction* can represent a sizable component of water consumption for a transportation system, these water components are out of the scope for this thesis, as we are primarily interested in examining how much water is required to operate a regional mobility network, not to construct one from scratch.

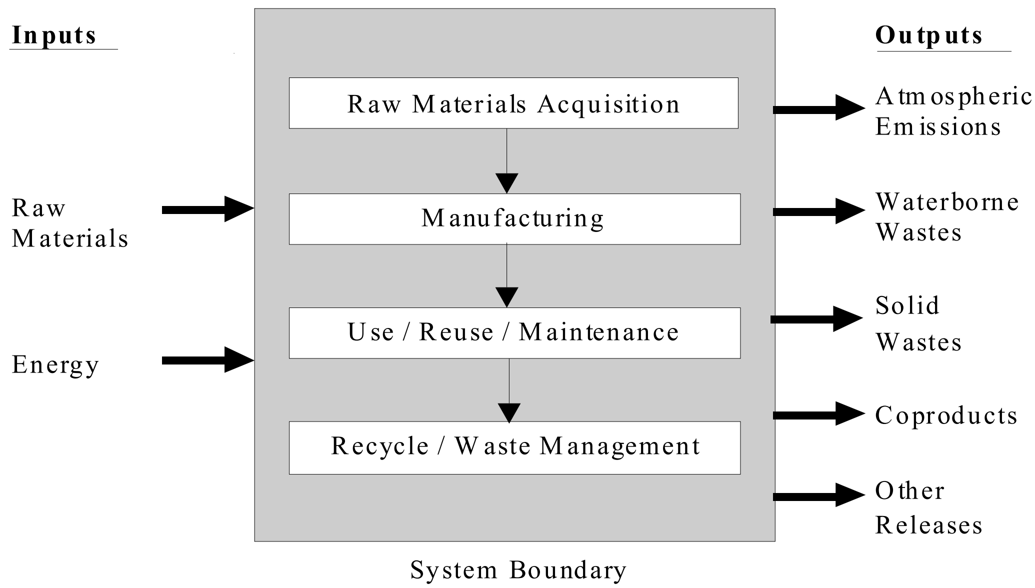


Figure 21. LCA System Boundary (Curran, 2006).

In addition to specifying a top-level system boundary regarding fuel, energy, and raw material inputs for the operation of a multi-modal transportation network, there are also material flows pertaining to the production of said raw materials and energy inputs, especially in terms of life cycle water flows from these individual pathways. The majority of assessments focusing on these individual fuels and energy sources refer to direct water inputs for fuel production or energy generation ranging from water injected for raw material acquisition and water withdrawn and stored for power plant cooling systems or steam generation (Gleick, 1994; Wu et al, 2009; Feeley et al, 2008). Additionally, there are other material input flows from which their manufacturing or procurement water requirements can be quantified (Sheehan et al, 1998; Spielmann et al, 2007; Chapagain et al, 2008), in which there is some direct water inputs for the raw materials and item flows that enter the system boundaries of fuel and energy pathways or infrastructure boundaries – for example, the procurement of gravel inputs for road resurfacing would involve some direct water flows.

Given that there is some amount of recursive water consumption for the top-level transportation system and its flows (in addition to corresponding material or energy flows that are inputted to create these objects), we need to be careful where to impose constraints regarding the extent of indirect water consumption to consider in this thesis. For example, if the system is not properly scoped, indirect water consumption of fossil fuels such as petroleum can ultimately be traced to water consumed by flora or fauna whose remains have been compressed and converted to raw fuel material over millions of years. Furthermore, the direct or indirect water inputs for some material and energy flows may not actually affect water resources for the region in which these materials or fuels are consumed, such as in having countries or regions with abundant water resources producing fuels or feedstock for areas with limited water availability (Allan, 1998; Wichelns, 2010). Consider, for example, a region that imports almost all of the raw materials required for its energy or fuel networks from other regions, such as for Georgia where the vast majority of fuel for transportation or power generation purposes is imported and which has no local fuel reserves (Energy Information Administration, 2010).

With that in mind, the primary constraint regarding direct and indirect water flows for the system of interest is that the only relevant water inputs assessed for a given region are material inputs that would directly affect local water availability. In other words, if a material or energy input for the transportation system is imported from another state or country, the amount of water required to produce or acquire this item is excluded from the model (this is not to say that "zero" water is required for these materials in this specific region; rather, the meaning of this exclusion is that the production or procurement of this imported system input may affect water resources in the region it was produced but not in the region in which it is used). Similarly, if the raw materials for energy sources or fuels are imported into a given region but are processed or converted locally within this region, we would consider the amount of water consumed for any production or refining of these components simply because these production facilities and pathways would need local water resources for their operations.

4.3. Traditional Structured Engineering Processes

The integration and management of elements and inputs such as the above multi-level components and water flows for a transportation system can be achieved via systems engineering, which in general is "an interdisciplinary approach and means to enable the realization of successful systems" by "integrat(ing) all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation" (INCOSE, 2004). Traditionally, conventional designs and systems have been based on a document-centric approach where all relevant information on a system or component is embodied within a series of lists or charts within documents or written specifications that are exchanged between developers and stakeholders (Friedenthal et al, 2008). This document-centric approach has commonly been coupled with systematic engineering design processes, from which solutions or optimal designs are systematically developed from defining requirements based on given criteria or surrounding environment to evaluating potential solutions based on said requirements. For example, all requirements can be allocated into a coherent list, from where solutions are developed either discursively through a series of selection charts and tables or intuitively through brainstorming to form a concept. This concept would then be embodied into a preliminary design based on an exhaustive analysis of technical and economic criteria, weak spots, cost optimization, and other factors, from which documentation and specifications would be created for the completed design (Pahl and Beitz, 2007; Motte, 2008).

Other traditional processes exist for developing designs or system structures, such as the Vee, or "Technical Aspect of the Project Cycle", model where the requirements-driven system development process is broken down into system definition in order to decompose a series of requirements to develop system concepts (with iterative synthesis and agreement on system definitions) from top-level to bottom-level architecture, from where engineers conduct verification and component integration via a bottom-top approach to create a coherent, verified system structure. Much of the Vee model has been build with concurrent development in mind where concurrent studies and analyses can be conducted to "manage opportunities and risks inherent in higher level requirements" (Forsberg and Mooz, 1998; **Figure 22**). Since the transportation network of interest in this thesis consists of multiple levels and components with individual water components, the Vee model for systems engineering can be applied to trace individual water consumption in terms of detailed specifications and individual system components such as specific powertrains or fuels.

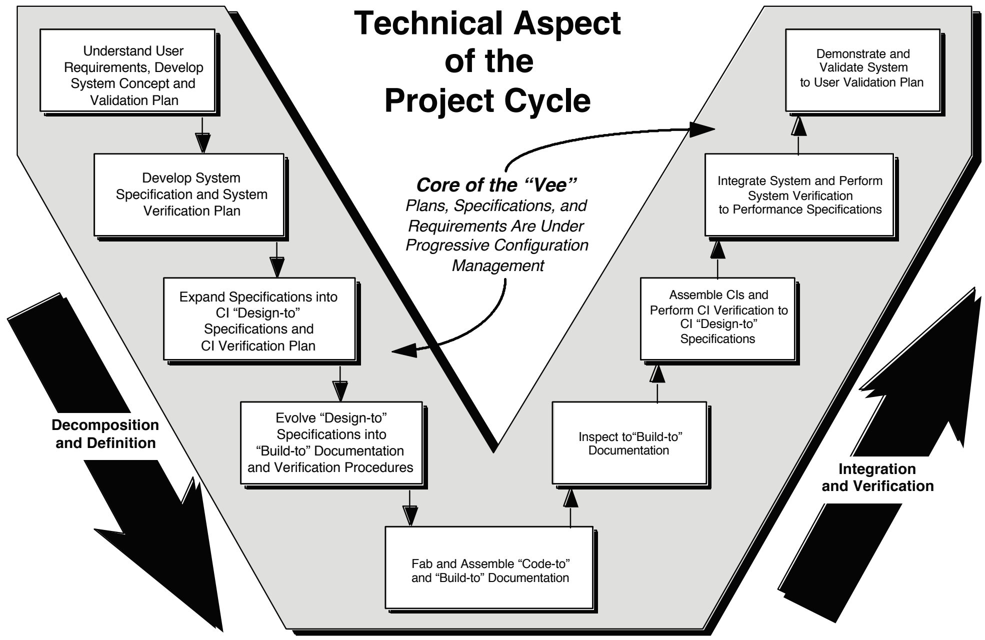


Figure 22. The "Vee" Model (Forsberg and Mooz, 1998).

That said, there are several issues pertaining to these two conventional engineering processes. As the systematic engineering design process model was developed several decades ago, the core of the process model is on qualitative information in terms of synthesizing stakeholder requirements or developing potential solutions. Other criticisms of the systematic engineering process model include the lack of "one-on-one correspondence between functions, organs (function carriers), and components" and that developing and selecting solutions based on preset criteria require some initial embodiment and consideration of other factors (Motte, 2008). Additionally, the above Vee model requires an iterative and linear approach, with the key assumption that a project progresses sequentially without any reverting to previous tasks. This leads to one important drawback of the Vee model as pointed out by Liversidge (2005), where he states that despite the well-defined development process structure and documentation-driven environment that the Vee model entails, there is little to no room for alterations in development or project plans, especially in cases of software development for large-scale systems where the model does not sufficiently adapt to any incremental changes or has disconnects between unit-level verification and top-level testing (Liversidge, 2005). Azevedo (2010) also points out that the lack of a quantitative structure within either the Vee model or the Pahl and Beitz method poses potential issues in allocating quantitative data for urban mobility systems as much of both methods' structures is based on documentation (Azevedo, 2010). Overall, document-based systems engineering and design approaches are not particularly suited for analyzing existing systems where quantitative results are more pertinent than building up a system from scratch.

While some elements of both engineering processes, such as defining structural architecture and functions and evaluating potential solutions or scenarios, are integral to the implementation of this water consumption model, these methods alone are not enough to quantify and assess water impacts for urban transportation. Another method is required in order to trace water consumption and to provide explicit information for differing regional conditions for transportation.

4.4. Model-Based Systems Engineering

One potential set of methods that can be applied to the research questions posed in Chapter 2 is the set of principles known collectively as Model-Based Systems Engineering (MBSE). As mentioned in that chapter, MBSE principles involve modeling in order to support requirements, design, verification, and other processes within systems engineering in order to improve specifications, design integration, and component reuse (Friedenthal et al, 2008). Much of MBSE revolves around a system model developed with a modeling tool or language and stored in a model repository, where elements such as requirements, functions, parameters, and structural properties can be stored, reused, and associated via connectors and other forms of relationships. Multi-level systems developed via MBSE principles can store information for more efficient traceability and sharing of knowledge, which Azevedo (2010) notes can be potentially useful in managing multi-scale components within a large system.

The premise for model-based environments is that models “represent an excellent way to visualize one or more aspects of a system” despite the observation that not all complex systems can mirror their mission requirements clearly (Ogren, 2000). From these models, engineers can facilitate analyzing requirements, defining the system structure and functions, as well as developing and verifying these designs; all of these stages in systems engineering can be viewed graphically within an information or system model (Baker et al, 2000). Compared to document-centric design methods, model-based design methods employ a consistent structure that “provide(s) clear and unambiguous definitions of behavior, capability, or design” where relationships and connections between elements and associated data are clearly shown and traceable back to system requirements or verification (Baker et al, 2000). These benefits are even more apparent in multi-level, complex systems where allocations and connections between numerous system-level requirements and thousands of system components cannot necessarily be verified or represented accurately in document form.

4.4.1. Overview of MBSE Methods

Just as there are several existing systems engineering methods for traditional approaches, there are several existing MBSE methods that have been augmented from conventional systems engineering methodologies, as Estefan (2008) details in a broad survey of commercial and open-source methods. One particular method of interest that combines traditional systems engineering methods with an object-oriented modeling environment is the INCOSE Object-Oriented Systems Engineering Method (OOSEM). The OOSEM approach, which can be implemented via numerous modeling tools such as the Systems Modeling Language, incorporates a top-down approach "to support the specification, analysis, design, and verification of systems" where object-oriented concepts are integrated with traditional systems engineering methods (such as the Waterfall or Vee processes) in order to facilitate analyzing stakeholder needs, defining system and subdomain requirements, defining and synthesizing logical architecture and its candidate alternatives, evaluating these alternatives, and verifying the entire system (Estefan, 2008).

The basic premise of OOSEM is that every system is composed of defined objects that have specific attributes, parameters, and constraints, from which these objects can be tied to specific functions and can contain unique metrics or measures of performance (Ryder, 2006). A logical architecture can be constructed that consists of the system's functions and behavior, from which the defined objects within the system model can then be integrated and allocated into several candidate physical structures (Friedenthal et al, 2008). At the same time in developing and synthesizing the logical and physical architectures within the system model, the OOSEM process also requires optimizing these alternatives and tracing system components back to their requirements in parallel, where the intent is to facilitate continuous capturing of requirements allocations and relationships as well as to capture parametric components and perform engineering analyses throughout the development process (Friedenthal et al, 2008).

Other MBSE methods include more software-oriented approaches such as the Harmony-SE method, from which the key objectives are to determine top-level system functions and to "identify associated system states and modes", from which these functions and modes are synthesized into a physical architecture (Estefan, 2008). Another methodology geared for Model-Driven Systems Development is the IBM Rational Unified Process for Systems Engineering, which is a process framework based off of the Rational Unified Process methodology designed for "assigning tasks and responsibilities within a development organization" for software engineering (Rational, 2001). The key objectives of RUP – managing requirements, developing component-based architectures, developing software iteratively, abstracting software to models, verifying software quality, and managing revisions – are revised in the RUP-SE method for a systems engineering environment. On the other hand, the Vitech MBSE methodology consists of linking four systems engineering activities – source requirements analysis, architecture and synthesis, functional and behavior analysis, and design verification – are "linked and maintained through a common System Design Repository" where they are connected to associated domains – for example, the synthesis of system architecture would be linked to an architecture domain detailing the structure of the system (Estefan, 2008; Vitech, 2010).

4.5. Reusing Components in System Models

In many development processes for systems or components, it is common to derive similarities between elements within the system such that these components or entire subsystems can be reused, of which multiple components of a similar structure or context can be leveraged from or described via a single class or object element (Karban et al, 2009). Previous research involving Model-Based Systems Engineering applications has stressed the need to reuse modular components and subsystems within said system models and repositories. This is very similar to the concept of modular products and size ranges, where Pahl and Beitz (2007) note that size ranges for a particular design can reduce design work and increase repeatability in manufacturing and implementation by implementing similar geometric configurations and a basic design for a uniform solution principle; in terms of modular products, where a single function can be achieved through the assembly or synthesis of multiple individual functional units (Pahl and Beitz, 2007). The same can be said of other domains such as software systems, where a transition to a product line approach where product variations are developed through changes in requirements or criteria can lower development times and increase overall quality (Diaz-Herrera et al, 1995).

The concept of reusable components has been central to several research efforts in improving or augmenting design processes across multiple disciplines. Such an idea has become a starting point for streamlining software development, for example, in which in an attempt to improve productivity and quality similarities within multiple software systems or components can be "capitalized" to build new or improved software designs with existing artifacts (Ali et al, 2004). Such individual components can effectively be stored in repositories and libraries based on pre-defined classifications in terms of keywords, facets, or functions within a system's domain, where these elements are developed with a formal, standardized language or specification and can be utilized by designers or developers to help achieve desired functions for systems or components (Karban et al, 2009; Ali et al, 2004; Paredis et al, 2000). As Azevedo (2010) points out, many of these sub-models or sub-systems within a complex system can be described within a set of modular components, especially if they share similar pathways; he points to fuel production pathways for vehicles for differing classes and proposes that to analyze a complex sustainable system inventories of energy sources can be broken down into individual, modular parts that would facilitate a more clearly-defined structure (Azevedo, 2010).

In addition to implementing reusable components by defining modular objects through a domain-specific language, model reuse can play an integral role in reducing the complexity of analyses of complex systems. Jobe (2008) proposed that engineering analysis models can be configured for reuse by modularizing components and subsystems within said models, where in large-scale models groups of sub-models can be organized effectively within Multi-Aspect Component Models (MAsCoMs) that describe a system or component through multiple perspectives (Jobe, 2008). In terms of simulation-based design, analyses and simulations conducted during the product development cycle can be realized by implementing standard or modular components that can be configured into multiple variations depending on the stage of the design process (Paredis et al, 2000).

Ultimately, model reuse can streamline the development and analysis of behavior and structural models pertaining to complex systems, as these systems can now be expressed or represented as a series of modular objects where multiple system elements can be described by common components such as core requirements, functions, or physical artifacts taken from domain-specific component repositories or libraries.

Reusing common or similar model elements can potentially reduce model development time and allow developers and stakeholders to utilize design knowledge effectively while improving quality and model performance.

4.6. Applying Model Reuse to Transportation Systems

As previously noted, system components sharing similar properties or characteristics can be characterized by model objects that can be reused for multiple configurations or scenarios. We can expand this observation even further to water consumption, where many of the above assessments on water consumption for energy and transportation fuels allocate water usage in terms of extraction, processing, and distribution, along with similar intermediate processes such as transportation (**Figure 23**). While some fuels such as biodiesel and ethanol are extracted using different methods (such as converting extracted oil into usable fuel) and are procured from energy crops, and while some transportation fuels such as compressed natural gas require additional processing or preparation at fuel stations, all of these fuels can attribute water consumption to these three main processes.

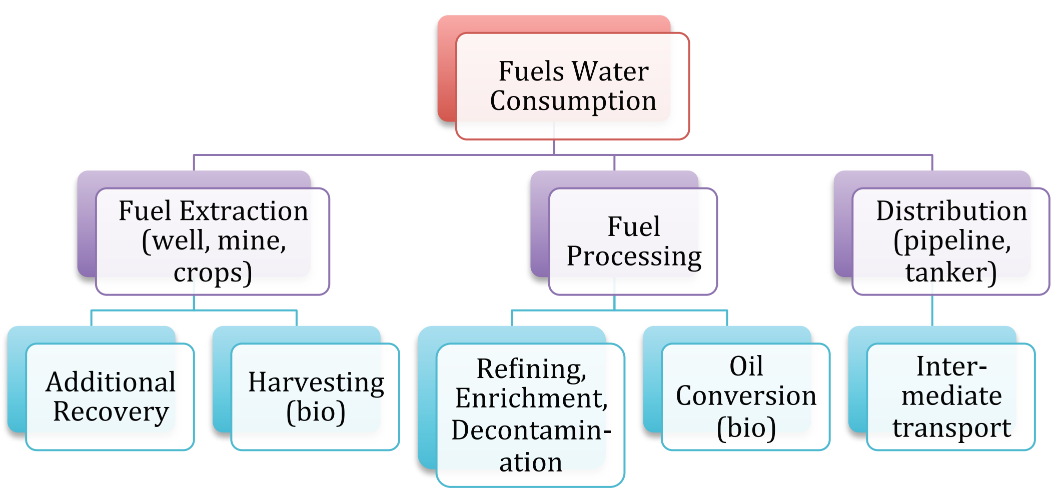


Figure 23. General Breakdown of Water Consumption for Fuels.

A more concrete example of modularity is the water consumed in maintaining and operating these vehicles as well as any supporting infrastructure in this transportation network. We previously hinted that water consumption for a vehicle's maintenance components and infrastructure can be traced to water required for producing the fluids necessary for a vehicle's operation; with the exception of electric vehicles where there is no powertrain lubricant, all vehicle types – petroleum-fueled or biofuel-powered, passenger vehicle or transit bus – have the same types of powertrain and hydraulic fluids ranging from coolant and antifreeze to engine lubricant, albeit with differing amounts stored/consumed within each vehicle. Similarly, any service infrastructure within a transportation network is expected to share similar components and processes for multiple transportation modes, which would necessitate the implementation of modular components to be applied across multiple variations of transportation modes.

4.7. Object-Oriented Modeling and an Introduction to the Systems Modeling Language

As computer-based models become widely commonplace in the design and analysis of complex systems across multiple fields and industries, many systems developers have examined ways to express such complexity through reusable and modular elements in order to reduce development time and improve model quality. As previously mentioned, this is particularly important in system representations such as that of multi-modal transport and mobility networks. One potential way to implement and reusable elements and multiple configurations and variations of transportation modes within an urban transportation network is the **object-oriented modeling** approach, where a problem or system is represented as a set of objects or individual data structures containing certain properties and attributes, from which these objects can be reused, inherited, or augmented to construct sub-systems or larger components.

As with the concept of model reuse and modular objects, components or structures described using object-oriented programming and modeling concepts would need to be described by a common set of semantics for model representation, or a formalism, in order to construct and analyze a consistent system model (Luh, 1994). This is the premise of the Unified Modeling Language (UML), which is a language that facilitates the specification, visualization, and documentation of software systems in terms of requirements, structure, behavior, and other characteristics of a system to be designed (Object Management Group, 2010). While UML can be directly used to model other systems such as enterprise systems, there are several constructs specific to systems engineering principles – such as verifying requirements and quantitatively analyzing system architecture and behavior – that cannot be described by UML itself. As such, the SysML language was created to support systems engineering tasks via object-oriented principles in developing complex system models.

Friedenthal et al (2008) define SysML (the Systems Modeling Language) as a general-purpose graphical modeling language that supports the analysis, specification, design, verification, and validation of complex systems" for a broad range of applications ranging from hardware, software, facilities, and other manmade or natural systems. This modeling language (or "class", in UML terminology) itself is a subset of a broader language context or "metaclass" (the Unified Modeling Language in this instance), from which SysML leverages certain elements while introducing or heavily revising others. SysML can graphically represent systems and components based on their structural composition, function-based activities or behavior, quantitative constraints or parameters, and relationships between defined functions or structure to initial stakeholder requirements, with the relationship between SysML and UML as shown in **Figure 24**.

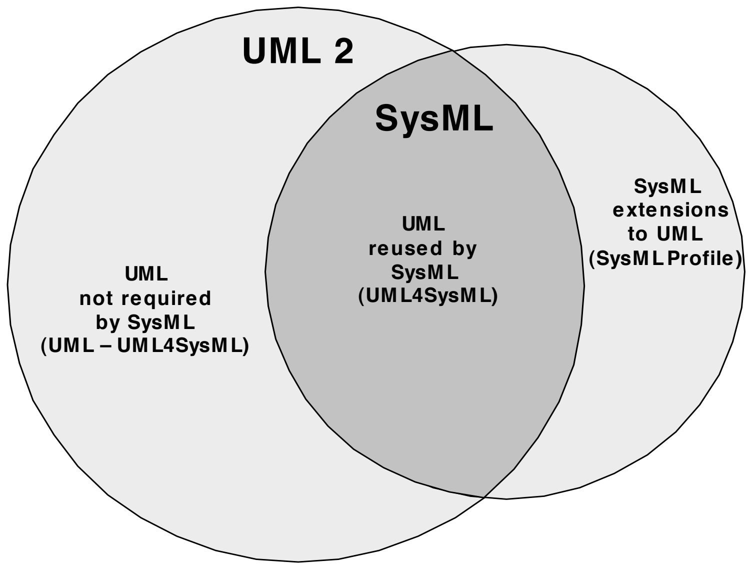


Figure 24. Relationship between SysML and UML (Object Management Group, 2010).

The current specification for SysML (Version 1.2) dictates that the language is a subset of UML 2 and extends the Unified Modeling Language to support Systems Engineering tasks, such as satisfying task requirements and verifying measures of effectiveness and system metrics. Unique to the Systems Modeling Language as compared to UML are the following elements:

Requirements: A requirement specifies a condition or function that is to be satisfied (either as a demand or as a wish set by the customer or stakeholders) (Object Management Group, 2010). These text-based elements can specify a function or a constraint that the desired system must (or should) have, and these requirements can either be elaborated through sub-requirements (via a relationship defined as containment) or through cross-cutting relationships (allocations) that link or associate one requirement with another different requirement specification. These requirements can be shown in graphical form (via a requirements diagram) or tabular or matrix form.

Parametrics: Another set of elements unique to SysML are parametric elements such as constraints that can be imposed on quantitative values or characteristics within a system model in order to facilitate analysis and verification within that model (Friedenthal et al, 2008). The basic element of interest is a constraint block, which integrates engineering analyses with SysML models by specifying mathematical expressions that are linked to numerical parameters specified for structural elements within a system.

Other sets of elements that are either leveraged or revised from the UML specification include structural elements such as the following:

Structural Blocks: Blocks are defined as modular units that has a collection of properties or attributes that describe a system of interest and can be used throughout the systems engineering process to store relevant properties, operations, and relationships in terms of physical structure (Object Management Group, 2010). As a basic component of SysML, blocks are a revised version of the UML class element, with some attributes such as specialized associations removed in SysML and reusable constraints and connector properties added into SysML. Blocks themselves can be structured with **part properties** and **value properties**, which can be used to specify a certain subsystem or component in the context of the abstract definition noted with a block. Value properties serve as internal parameters for a block and can be used to specify input variables such as mass, length, volumetric values, or even text; the nature of each property is specified by a **value type** that contains information on the kind of quantity described and associated unit. Like any basic element, SysML blocks can be composed of other blocks or can share certain relationships. Blocks and their associated relationships are graphically described within a Block Definition Diagram, while a block's internal workings and physical flows can be specified even further within an Internal Block Diagram.

Ports and Flows: Flows of items and messages from one block to another can be specified with ports for each block and connectors that link one port on one block to another port on a second block, with the intention of allowing the development of modular and reusable block elements (Object Management Group, 2010). Ports can be defined as standard points, which specifies the services that a block has for its surrounding environment as well as any services that the block requires from its environment, from which blocks can call operations or send signals through these ports. Ports can also be defined as flow powers, where the input and output of items from a block to its environment is specified. Additionally, objects flowing between structural elements can be specified by item flows such that blocks and parts can be interconnected based on related flows and usage.

Additionally, SysML has the capability to model behavioral elements ranging from functional or message-based interactions to discrete behavior within a system. Functions within a system can be described as **activities**, just as with UML; activities are modeled with inputs and outputs of control message or objects along with sequences and conditions. **Interactions** can describe message-based interactions between two or more entities within a system with defined flows of messages from one block or actor to another within a sequence diagram, while discrete behavior can be described via **state machines** along with associated transitions between one state (such as an operating state) to another (idle state, for example) within a part or subsystem. The relationships between these types of elements can be seen in **Figure 25.**

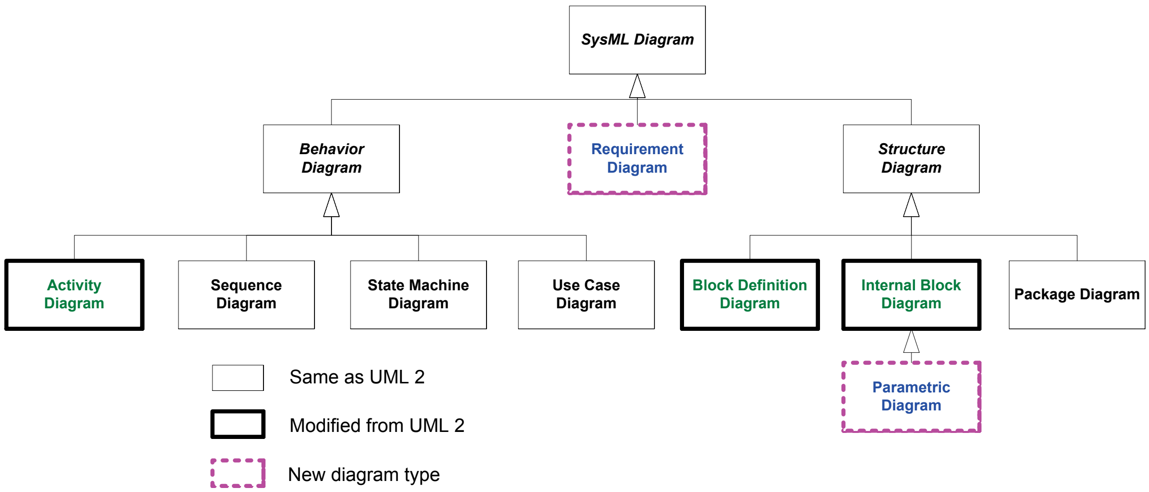


Figure 25. Breakdown of SysML Diagrams (Object Management Group, 2010).

Relationships such as **compositions, associations, or references** between blocks can be represented in a **block definition diagram** that illustrates blocks in terms of their features and associations – these diagrams can represent either a subset of the model or simply a certain block. Parameters and calculations within a model can be described with **parametric diagrams** that can include **part properties** from their respective blocks, **constraint blocks** that describe mathematical expressions, **ports and connectors** that indicate the relationships between value properties and constraints. The blocks themselves also serve as descriptions for **instances** or objects that exhibit the same features as those of blocks. In our model, instances are used to store values and parameters that are unique to a certain regional environment, while these values and parameters are specifications of the properties defined in their related blocks.

It must be noted that these graphical elements – blocks, properties, constraints, activities, flows, and diagrams – are merely a representation of a much larger model. The diagrams themselves are not sufficient to describe the system of interest; instead, they serve as “windows” to this system. The complete definition of the model within SysML is accomplished with a **containment tree** that stores **packages** (folders) containing these blocks or properties. Packages themselves can be structured into a hierarchy that can be cased on system hierarchy or complexity, process life cycle, related model elements, and more (Friedenthal et al, 2008). The relationships between parent packages and child packages can be described by **containment relationships** within a **package diagram,** which is simply a graphical representation of the hierarchy defined in the model.

4.8. SysML As A Tool for Model-Based Systems Engineering

As a language designed for systems engineering applications, SysML and its elements described in the above section – structural block elements, activities, interactions, parametric constraints, and requirements – can capture information effectively within modular model components in order to support Model-Based Systems Engineering in addition to systems engineering as a whole. Given that there are multiple stakeholders and multiple disciplines involved in the systems engineering process, it is inevitable that each discipline will have unique methodologies in developing and assessing systems such that no other stakeholder in the process would be able to understand. Even so, designers need to build upon results obtained by developers in other disciplines and need to be able to synthesize results that can be understood by everyone else in the decision-making process (Pahl and Beitz, 2007). This is where SysML and UML come in, as it can unify system descriptions and streamline interdisciplinary communication in terms of system structure, requirements, and verification -- regardless of imposed methodology or differing disciplines – in order to manage increasingly complex systems (Balmelli, 2006).

Specifically, for model-based systems engineering, SysML has the capability to capture top-level stakeholder requirements and trace or satisfy them to corresponding structural or functional elements for the system of interest, from which multiple viewpoints or alternatives can be developed within a model. This is also in conjunction with SysML's capability to reuse model elements "where textual requirements can be parameterized and properties formally typed" as well as formally reused to develop a consistent specification across multiple projects (Karban et al, 2009). Another benefit of SysML as an integral component for MBSE is that the standardized and comprehensive specifications allow for a consistent and unambiguous representation of system model components (Willard, 2006). Additionally, SysML – as a graphically based modeling language geared for systems engineering purposes – is especially useful in specifying structure, behavior, requirements, and constraints on quantitative or qualitative properties in systems, from which systems and associated domains can easily be decomposed and allocated such that individual objects within the system model can be traced and clearly defined (Linhares et al, 2006; Grobhstein et al, 2007). In other words, the relationships and connections that system developers can specify within a SysML model allow for a graphical decomposition of a system to its sub-systems and individual components, aiding in individual requirements tracking as well as overall traceability – a must in managing complex systems where all levels of requirements must be satisfied across hundreds or thousands of parts (Culler, 2010; Hause, 2006). These qualities and capabilities have been applied to a wide variety of systems engineering problems such as in conducting reliability analyses of complex physical systems (David et al, 2010), applying model reuse within an Active Phasing Experiment project for telescope control systems (Karban et al, 2009), modeling continuous system dynamics for hydraulic pump components (Johnson et al, 2007), as well as in assessing life-cycle flows of manufacturing processes and sustainable systems (Culler, 2010; Azevedo, 2010).

Ultimately, SysML was developed from the beginning to support and streamline the development of complex systems via a systems engineering context that encompasses specifying requirements, developing a logical and physical system structure, as well as in assessing system components via parametric evaluations for a given system model. Furthermore, the flexibility and breadth of SysML components, along with the ability to define model elements with formal properties and characteristics and to reuse these objects to describe multiple variants or viewpoints, allows for the modeling language to be applied to projects or systems across multiple fields. Furthermore, the consistent formal definition of language elements such as requirements and activities can be particularly useful in developing system models focused on life cycle impacts and flows, where properly defined structural and functional objects within a SysML-expressed model reduces uncertainties in terms of modeling domain, goals, and constraints against boundary-level assumptions (Azevedo, 2010).

That said, there are some drawbacks of SysML that should be noted before moving on. First and foremost, the open-ended nature of SysML – in the sense that SysML is not tied to a specific MBSE methodology – leads to criticism regarding that SysML has no formal approach to modeling with regards to a clearly defined model development process or scope. As Culler (2010) points out, this flexibility can lead to unintended ambiguity in that SysML modeling elements may be used in one way by one modeler and in a completely different way by another individual (Culler, 2010). Another notable drawback that has been observed in SysML models is that its graphical nature may result in difficulties in viewing component relationships and individual elements for a complex system; for example, when comparing against other system modeling languages such as the Object Process Methodology approach, Grobhstein et al (2007) observed that the holistic OPM approach with one-to-one mapping between hierarchical diagrams and textual representations was easier to comprehend against the multitude of diagrams utilized to describe the same system within SysML (Grobhstein et al, 2007). Furthermore, as SysML is heavily based off of the Unified Modeling Language specification, a key prerequisite for stakeholders and developers to understand or to build upon a SysML-based system model is to have some working knowledge of the UML language and SysML extensions themselves, which may hinder large-scale adoption due to its steep learning curve (Linhares et al, 2007); similarly, with UML being in constant development with language maintenance and modifications, SysML's extended and leveraged components would need to be constantly updated and evolved, which would present a potential liability in developing concrete models and analyses (Willard, 2006).

4.9. Engineering Analysis Models

Although SysML as a language can be used to support Model-Based Systems Engineering, it in itself is not a tool or methodology. In other words, it is merely a way to apply MBSE principles without specifying a certain method; ultimately, systems engineers determine a method based on "which activities are performed, the ordering of activities, and which modeling artifacts are created to represent the system" (Friedenthal et al, 2008). This is of particular concern for this thesis in which the primary intent of this system model is to analyze the effects of implementing alternative vehicle modes and fuels into a transportation network with regards to changes in water consumption. While there is no one way to structure and verify a system within SysML, previous research into analyzing systems within a model-based environment have suggested that the system model's structural elements and analysis elements be decoupled, just as with the basic notion that a system model's structural and behavioral aspects be separated while applying MBSE principles to develop a system model (Azevedo, 2010). This is where engineering analysis models become invaluable components in verifying and assessing a multi-scale system such as that of the transportation network considered in this thesis. In many cases, complex systems may require multiple types of metrics to be considered such that building all of these assessments directly within a model's structure would be inefficient.

The basic premise of engineering analysis models, or EAMs, is that they are "knowledge-based abstractions of physical systems" in order to "predict the behavior of the product and/or its manufacturing processes for evaluation and optimization" in terms of intended functions or other specified measures of performance (Grosse et al, 2005). These analysis models, which may differ in scope or accuracy depending on when invoked or developed in the systems engineering process, can be characterized by three main factors - accuracy, resolution, and causality – and consist of elements that can be linked to a specific structural component within a system or left as analysis-specific values, along with a set of input data and outputs pertaining to parameters specified by suppliers (such as collected life cycle assessment data) or recipients (such as target values or calculation results) (Grosse et al, 2005). Similarly, analysis models play a role in the development of behavior models for simulation-based design where virtual prototyping is conducted to verify design requirements and specifications (Paredis et al, 2000). While engineering analysis models are critical components for systems engineering in being able to evaluate physical architectures and verifying system requirements, many preceding modeling languages did not provide any integration between system architecture and analysis components, which results in disjointed analysis models from their corresponding structural and behavior models and increased development times – this would certainly detract from the original intent of traditional systems engineering processes to streamline development and communication (Peak et al, 2007; Forsberg et al, 1998).

The need to analyze physical systems based on defined parametric values and quantitative metrics is the basis of much of the augmentation of UML to create SysML, as parametric elements in SysML were added mainly to support engineering analysis of "critical parameters including evaluation of performance, reliability and physical characteristics" (Peak et al, 2007). As such, analysis models in SysML can be developed by specifying constraints within block elements along with inputs and outputs (in the form of value or part properties) stored within structural system elements to be assessed. These parametric elements for analysis models have been based on the concept of composable objects, which are based on entities being composed of modular components or groups of components as well as object and constraint graph concepts to gain their modularity (Peak et al, 2007; Paredis et al, 2000); these objects ultimately contain quantitative and lexical components that can be interpreted by computer or software systems in addition to graphical elements that can be understood by modelers and users. For example, analysis elements such as constraints or mathematical expressions can be represented textually such that they can be passed from SysML to analysis tools, while to the user these elements can be represented as graphical objects in the form of *constraint blocks* such that they can be linked to system properties or variables. Just as with a hierarchical physical architecture where a block can consist of multiple blocks representing sub-level components, the modular nature of composable objects allows top-level analyses to be broken down into multiple lower-complexity analyses (Peak et al, 2007; Culler, 2010).

Engineering analysis models and their analysis contexts allow multiple stakeholders to assess parametric or quantitative elements within a system model without having any necessary constraints or parametric elements (apart from the value properties specified in each structural element) as part of the structural composition of the system model. Furthermore, since these analysis elements are separate from the structural aspect of the model, they can be kept in separate packages or even organized into libraries within the system model where they can be classified either as common constraints (such as straightforward mathematical operations, i.e. multiplying two values together) or as subdomain-specific constraints (such as calculating the tank-to-wheel efficiency of a battery-electric vehicle). Furthermore, as Azevedo (2010) notes, these decoupled analysis elements within a system model can be translated into other languages pertaining to specific analysis tools such as Mathematica and MATLAB, where a consistent method of information conversion (such as in conversion and analysis tools like ParaMagic) is used to reinterpret structural and parametric elements into tool-specific syntax (Azevedo, 2010).

4.10. Discussion

Ultimately, all of these methodologies are leveraged and augmented from one or more established methods pertaining to systems or software engineering; for example, the OOSEM and Harmony-SE methods leverage heavily from the "Vee" model while the RUP-SE method is leveraged from a software-based approach. More importantly, all of the above MBSE methods follow several primary activities (Estefan, 2008; Ogren, 2000):

- Specifying and synthesizing system requirements
- Determining behavioral functions within a system
- Defining a functional architecture in the system model
- Allocating physical components or objects to associated functions
- Conducting an engineering analysis of the physical and functional architectures
- Validating and verifying the system design
- Continuous tracing and management of system requirements

These overall activities are also very similar to the systematic engineering process model, in which a conceptual structure can be developed via abstracting system requirements and criteria as well as in defining system-level functions and component subfunctions, from which this design can be refined and honed through further evaluation of its architecture, or in which the conceptual structure can be validated via external criteria from the system's surrounding environment (Pahl and Beitz, 2007; Motte, 2008).

In terms of implementing MBSE methods into the Systems Modeling Language, SysML provides a set of modeling elements that help facilitate the implementation of the above systems engineering tasks within a well-defined system model through requirements traceability and capture, as well as through graphical relationships and allocations within a system's components and functions. Furthermore, the object-oriented modeling elements within SysML allows requirements, structural, parametric, and function components and interfaces can be consistently defined and parameterized – thus allowing these elements to be reused within one or more associated models (Karban et al, 2009).

As many of these MBSE methods share common principles with traditional systems engineering models such as the Vee model, along with the observation that SysML is neutral with respect to applied engineering methodology, MBSE principles instead of a single explicit method would be applied with SysML in order to consolidate life cycle water consumption for individual transportation modes and mobility network infrastructures ranging from road networks to fuel and energy pathways. The approach in integrating these components is leveraged from Azevedo (2010)'s research into modeling sustainable mobility systems via SysML, where MBSE principles were used to developing a reusable system model via the following process (Azevedo, 2010; **Figure 26**).

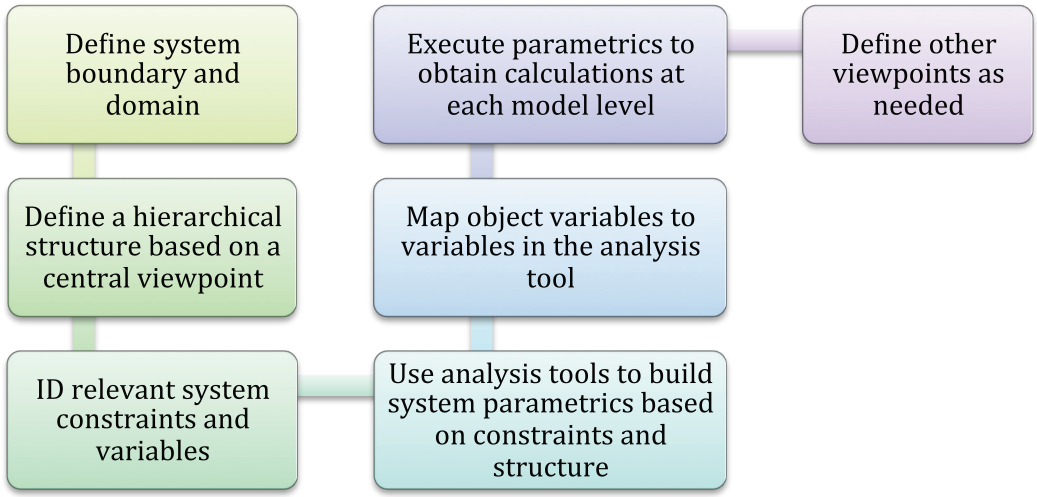


Figure 26. Model Development Process as specified in (Azevedo, 2010).

The above implementation process is geared towards a model context in which data from existing life cycle assessments are captured and stored into a model representing a physical system or network, from which such data in the form of parametric properties are linked to specified model constraints and are transferred to analysis tools for model verification or engineering analysis. In addition to the steps described in Azevedo (2010), the system model to be developed for this thesis will also include specifying requirements and constraints pertaining to the model structure and components to be assessed along with defining functional elements and physical flows for transportation modes and infrastructural elements within a transportation system in order to help determine where water consumption within this network can be traced, whether it is specified as object flows within defined actions required to sustain transportation fuel or energy pathways or as items flowing through a transportation mode or infrastructure's internal components. As such, in addition to building a hierarchical physical structure for a transportation system and for specifying parametric elements within this model that can be interfaced with analysis tools, this system model will expand on functional elements within a transportation network as well as in physical interactions between key elements within said network or system in terms of direct or indirect water consumption flows.

It should be noted that since the system model is intended to collect and analyze life cycle water consumption for individual transportation modes and infrastructure for a transportation network, the model is not necessarily a full-fledged system model. However, the flexible nature and object-oriented, reusable component environment of SysML, coupled with the structured methods of Model-Based Systems Engineering (and systems engineering as a whole) allows for an organization of information and components from other models and assessments that were constrained in the number of transportation modes and fuels or not spatially explicit for a given region. Given the large amounts of information regarding characteristics and material flows for multiple transportation and energy fuels in addition to multiple levels of transportation sub-systems and supporting infrastructure, it is important to have a structured and consistent approach to organize and modularize these elements in order to manage a complex, multi-modal system effectively, and MBSE principles/methods are a promising direction for developing such a structured and hierarchical model.

Even with the implementation of MBSE principles and SysML in constructing a complex system, there are some issues to address regarding using SysML effectively for systems engineering tasks. Take, for example, the analysis and verification process in the systems engineering process where the characteristics and performance metrics of system components need to be evaluated in order to compare with set requirements or constraints. However, given that there are countless mobility-related or water-related parameters of a multi-modal transportation system, it is important to select parameters and value properties that are “most relevant to the system’s behavior and the desired modeling viewpoints” in order to manage the system model and its structural or behavioral alternatives (Azevedo, 2010); this is especially important in attempting to develop a model and analysis viewpoint that can be consistently utilized to multiple regions with differing conditions.

CHAPTER 5

IMPLEMENTATION

5.1. Overview

In the previous chapter, a defined set of principles from Model-Based Systems Engineering and the System Modeling Language (SysML) was proposed as the underlying approach in developing a life-cycle water consumption model for a multi-modal transportation network. Based on the proposed approach, a multi-level system model can be developed incorporating object-oriented modeling principles, systems engineering tasks such as specifying functions and structure, and an analysis model consisting of parametric values and constraints that can be transferred to external analysis tools. As such, this chapter will describe the development and implementation of this model in order to assess vehicle and infrastructure use-phase water consumption for a given urban region. The chapter initially presents a hierarchical structure pertaining to individual transportation modes and their corresponding sub-systems as well as overall road infrastructure in terms of operation and maintenance required for supporting such transportation. From there, the set of governing mathematical constraints and relevant parametric values pertaining to each transportation mode, fuel, or other sub-domain in the model will be presented; these constraints and parameters are linked or attributed to a specific set of structural or analysis blocks within the SysML model.

Once the proposed hierarchical structure of the transportation network model has been discussed in detail, the chapter transitions to demonstrating the implementation of this conceptual model in SysML. This implementation starts out with specifying system-level and component-level requirements pertaining to what water consumption components or physical parameters/operations will be covered in this model. From there, water and material flows that have a significant amount of indirect water consumption are mapped for individual vehicle modes as well as for road and energy infrastructures. This leads to the structural definition of the model specifying the transportation system's domain and its components, from which value, part, and constraint properties for the analysis portion of the model can be defined. For this implementation, parameters pertaining to each vehicle type in terms of performance characteristics such as fuel efficiency are sourced from existing life-cycle models of transportation fuel pathways, while direct and indirect water consumption pertaining to fuels or vehicle operation and maintenance are sourced from other life-cycle databases as well as from the previous assessments discussed in Chapter 3. Similarly, for energy and road infrastructures, data for each regional scenario is sourced from local statistics pertaining to energy consumption and fuel distribution as well from statistics pertaining to vehicle market shares, road network length, average travel delays, and other spatially explicit information. Such data will be utilized in several regional scenarios posed in the next chapter.

5.2. Building the Structure for the SysML Model

As this thesis has focused primarily on water consumption stemming from road transportation modes and associated fuels/infrastructure, the SysML representation of a multi-modal transportation network will consist of the combined vehicle modes as well as the combined infrastructure required to support these modes (**Figure 27**). Ideally, a multi-modal transportation system model would include transportation modes ranging from road transportation to rail transportation and air/maritime modes; for this version of the model, the focus of the transportation system will focus on road transportation modes.

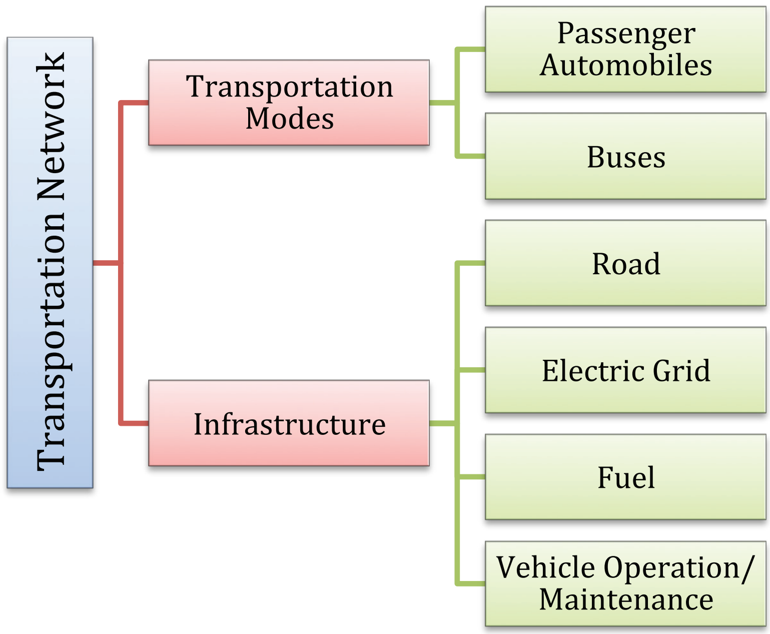


Figure 27. Top-Level System Heirarchy.

In this model, the top-level transportation modes in terms of road vehicles to be considered are passenger vehicles and public transit buses. Depending on the fuel types and vehicle configurations, either transportation mode can be further classified based on vehicle technology or fuel. For example, a set of passenger vehicles can be further organized into vehicles that run solely on petroleum gasoline, vehicles that run on biodiesel or ethanol, plug-in hybrid vehicles, and so on. Similarly, transit buses can be classified in the same way; for example, buses can be classified based on those that run on petroleum diesel, biofuels, or natural gas.

Based on this classification of vehicle technologies, two main vehicle technology classifications can be abstracted. Vehicle modes that run on fossil fuels (gasoline, diesel, or processed gases (CNG. LPG, or LNG)) or biofuels (ethanol or biodiesel), as well as hybrid vehicles that do not include any connection to the local electricity grid, can be combined under the category of "IC Vehicles", or internal combustion vehicles, since they all share common internal combustion powertrains – for example, biodiesel vehicles utilize slightly modified conventional diesel powertrains (National Biodiesel Board, 2011). Similarly, electric vehicles that require some connection to the local electricity grid in order to acquire energy for normal operation are grouped under "Electric Vehicles." Other vehicle technologies that either combine both types of powertrain technologies or employ other technologies would need to be separately defined – in this model, the additional vehicle technology included in the assessment is that of plug-in hybrid vehicles (PHEVs) which contain internal combustion and electric motor powertrain components and can either operate from grid-produced electrical energy or energy generated from their IC components depending on configuration (U.S. Department of Energy, 2010).

Of course, this top-level classification is somewhat simplified and omits some criteria pertaining to auxiliary internal components or manufacturability (which is not considered in this model). For example, hybrid electric vehicles (HEVs) include an electric motor and battery in addition to its internal combustion powertrain, which from a manufacturing perspective would differ from gasoline vehicle production. Similarly, some IC-based vehicle modes such as natural gas vehicles require additional modifications required to support compressed natural gas or liquefied gas. However, as the model is designed primarily for assessing life-cycle water consumption in terms of its *usage phase*, manufacturing differences such as in hybrid electric vehicles are omitted since HEVs take in petroleum or bioenergy fuels just as with conventional IC-based vehicles during their use phase. On the other hand, since natural gas vehicles have additional energy and material inputs during their use-phases (such as electricity and natural gas required for compression) compared to those of gasoline or biofuel-powered vehicles, these use-phase components will need to be addressed later on in the SysML structural model implementation (King and Webber, 2008 (1); Wang and Huang, 1999).

Figure 28 shows a graphical breakdown of the top-level hierarchy for the transportation modes to be assessed in this system model. For vehicles with internal-combustion engines, fuel technologies to be included range from conventional fuels such as petroleum gasoline and compressed natural gas (in addition to diesel for buses) to alternative fuels such as ethanol and biodiesel. For vehicles with electric vehicle powertrains, the "fuel" or energy source to be assessed will be the regional electricity mix – in other words, the distribution of thermoelectric and renewable power plants and associated fuels.

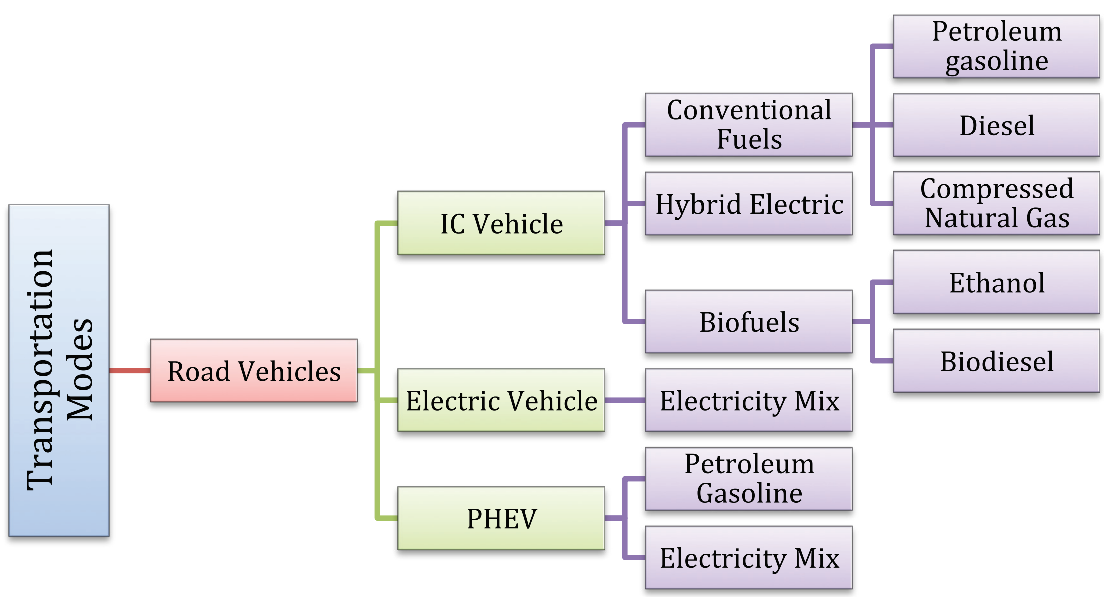


Figure 28. Transportation Mode Breakdown In Terms of Vehicle Types and Fuels.

5.2.1. Physical Breakdown of Vehicle Types

As observed in the Literature Review and Background in **Chapter 3**, water consumption stemming from the use-phase for passenger vehicles and buses can primarily be attributed to the fuels used. However, there are also several fluids within each vehicle that are required for a vehicle's normal operation, such as hydraulic fluid for a vehicle's power steering and breaking systems, motor oil or engine lubricant for an internal combustion engine, as well as coolant for the vehicle's powertrain system. Given that there are more use-phase material flows for a vehicle than just that of its energy sources, a physical breakdown of each vehicle type's components and systems is needed in order to allocate these flows and to trace their consumption or usage.

Each transportation mode assessed in this system model also has an associated internal structure that describes each vehicle's components and subsystems. For example, internal combustion engine vehicles can be broken down into powertrain, electrical, and chassis subsystems – the vehicle powertrain, for example, consists of the engine and drivetrain components such as the transmission, driveshaft, and differential; for this model, fuel-related components within the vehicle such as storage tanks are included under powertrain components as well. The chassis subsystem can be broken down into the vehicle's wheels and associated components.

Figure 29 shows the physical breakdown of an IC vehicle's components and subsystems that are relevant to water consumption and auxiliary flows such as for its fuel and lubricant; in this general breakdown, there is no distinction among gasoline-powered vehicles, biofuel-powered vehicles, and ethanol-powered vehicles as this is a high-level breakdown of the vehicle's physical components and that there is little significant difference among these three vehicle types. For natural gas-powered vehicles, the most significant physical difference is the inclusion of a set of cylindrical tanks required to store compressed or liquefied natural gas. While there is additional compression required for intermediate fuel storage, such compression is done at fuel stations instead of on the vehicle itself as the fuel inputted in the vehicle is pre-compressed or liquefied.

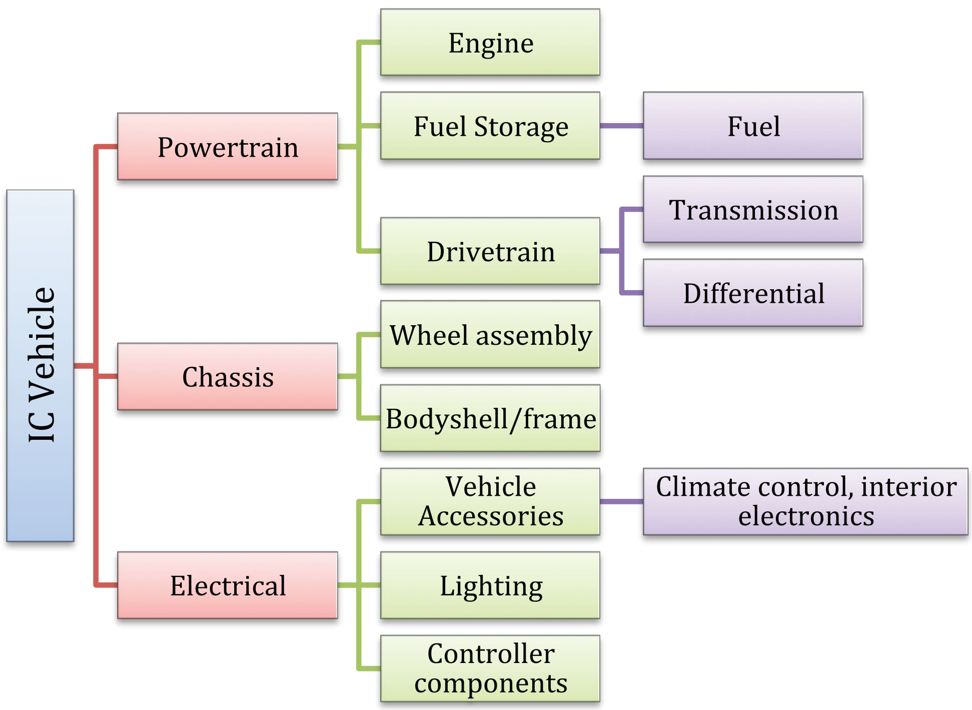


Figure 29. Physical Breakdown of Relevant IC Vehicle Components.

Electric vehicles share a similar structure with that of IC automobiles, with the primary exception that they consist of different powertrain components as well as a incompatible fuel source. Electric vehicle powertrains instead are composed primarily of an electric motor and battery pack instead of an internal combustion engine (this is not applicable to plug-in hybrid vehicles, which amalgamate an internal combustion powertrain with an electric drive subsystem). These revisions are summarized in **Figure**

30, where it is assumed that apart from the powertrain components electric vehicles share common chassis and electrical components as well as drivetrain components.

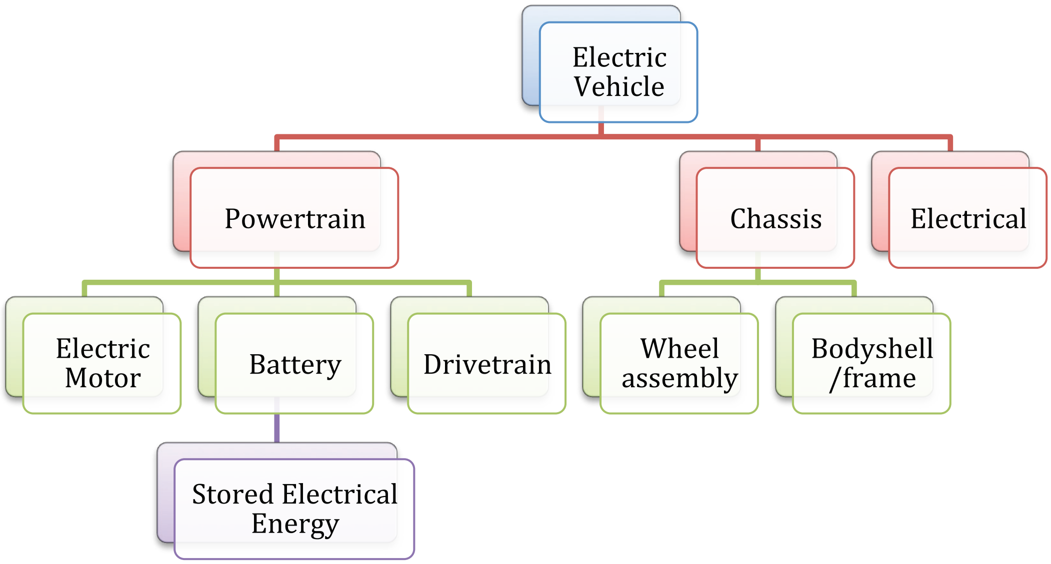


Figure 30. Physical Breakdown of Battery Electric Vehicle Components.

Additionally, a physical breakdown of plug-in hybrid and hybrid-electric vehicles can be specified. Both vehicle types contain battery and motor components in addition to internal combustion powertrain components. The key difference between the two in terms of use-phase material or energy flows is that while hybrid electric vehicles are independent of regional grid electricity and charge their batteries through regenerative braking or engine inputs, plug-in hybrid vehicles can charge batteries directly from the electric grid or through electricity generated from braking or engine inputs, in addition to being able to run solely on its internal combustion powertrain components. As with electric vehicles, this model assumes that these are the primary changes in the vehicle types' physical compositions; the physical hierarchy of hybrid vehicles can be summarized in **Figure 31.**

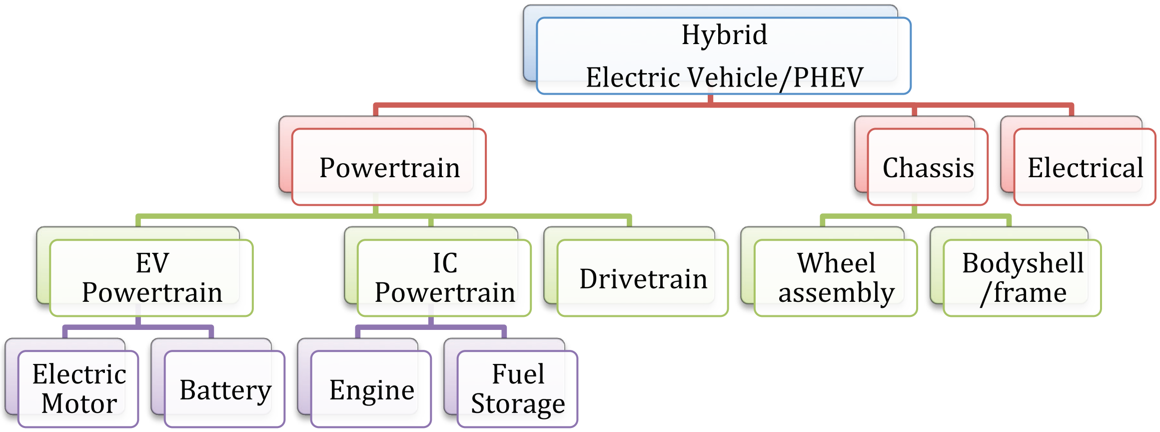


Figure 31. Physical Breakdown of Hybrid Electric/Plug-in Hybrid Vehicles.

5.2.2. Infrastructure Breakdown

The next structural hierarchy to be considered in this model is the infrastructure of the transportation network being considered. The infrastructure being assessed includes facilities and distribution networks for **fuel production** and **energy generation**, facilities required for **supporting urban mobility** including road infrastructure and mobility hubs, and infrastructure required for transportation mode **maintenance** such as service facilities. The following subsections discuss the structural hierarchy for these infrastructural components.

5.2.2.1. Energy Infrastructure Breakdown

Previous assessments on energy generation and associated water consumption for the United States breaks down power generation into thermoelectric plants requiring fossil fuels or equivalent fuels as well as renewable plants that generate electricity via wind, solar, or hydroelectric power (Merson et al, 2006; Feeley et al, 2008; Gleick, 1994). Fuels that are required for thermoelectric plants include coal, petroleum, uranium for nuclear plants, and natural gas; additionally, some regions also include electricity generation from wood waste and biomass as part of its electricity network (Gleick, 1994; Energy Information Administration, 2010).

Similarly, renewable power plants for this model pertain to electricity generation sources that do not require combustion of any fuels; as such, renewable power generation in this hierarchy includes only hydroelectric dams, wind power, and solar power. While solar power can be generated either from photovoltaic panels that directly generate electricity or from concentrated solar towers that generate electricity from steam turbines from a heat engine or working fluids such as molten salt (Harto et al, 2010), the model at this stage will consider photovoltaic solar power only. Renewable fuels such as biofuels and other forms of biomass (such as wood waste and switchgrass) are grouped under thermoelectric power generation, as theses fuels need to be combusted for steam production and subsequent power generation.

Additionally, an electricity network also includes a network of power transmission and distribution components as part of the region's electric grid. These distribution components include transmission lines, transformers, power substations, and distribution lines (U.S. Department of Energy, 2004; **Figure 32).** While some water is required for normal operation and maintenance for these grid components – either through direct water inputs or water used in the production of fuels and electricity needed for such maintenance – these components are not included in the structure of this model; however, as there are potential losses resulting from the transmission of produced electricity from power plants to end-consumers, this transmission efficiency is the key performance metric for this system model (Campanari et al, 2010).

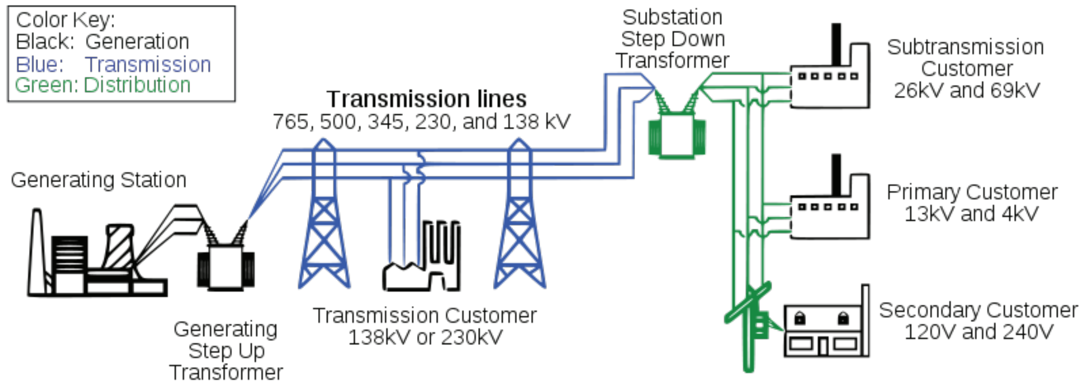


Figure 32. Schematic of Electric Grid (Transmission and Distribution Components are Colored) (Source: Global Energy Network Institute).

The top-level hierarchy of a transportation network's electrical grid infrastructure can be described in **Figure 33**, where the infrastructure is broken down into thermoelectric power generation, renewable power generation, and electricity transmission components. Additionally, the power generation groups are further classified based on fuel source for thermoelectric plants and based on plant type for renewable power generation.

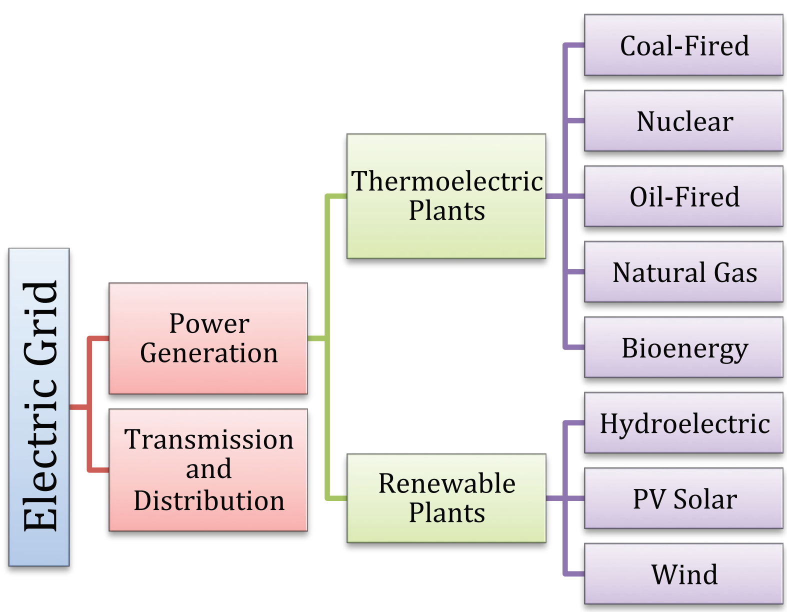


Figure 33. Electric Grid System Hierarchy.

Water consumption for thermoelectric power generation, as discussed in **Chapter 3**, has been traced to water inputs for a plant's cooling systems and cleaning as well as water required to produce or process the fuels required for these plants (Feeley et al, 2008; Merson et al, 2006; Fthenakis et al, 2010). Additionally, water inputs for thermoelectric power plants can be traced to other components within thermoelectric power plants, where some water is extracted from a source into a plant's boilers for steam generation to be passed through the plants' steam turbines as well as for other water-intensive processes, although the majority of water consumption rests in water consumed or evaporated as cooling water (Gerdes et al, 2008). Based on these observations, a physical breakdown of thermoelectric power plants are shown in **Figure 34** where the relevant components of such infrastructure include cooling components such as cooling towers as well as steam production components such as boilers, heaters and condensers, and electricity generation components such as steam turbines. It must be noted that while there are water flows for both sets of subsystems for these power plants, water consumption data for these plants are cumulative and are primarily focused on consumptive losses from the plants' cooling systems.

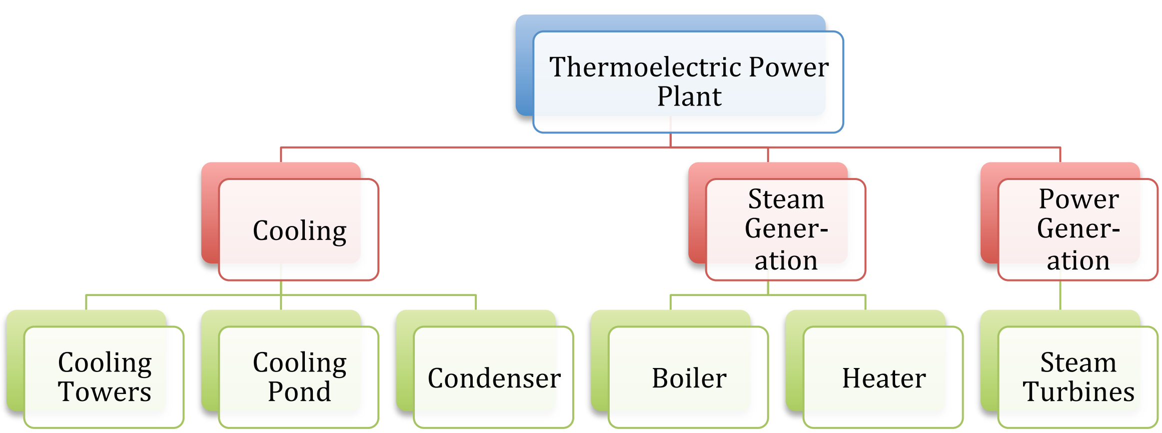


Figure 34. Physical Breakdown of Thermoelectric Plant Components.

Based on the above breakdown and previous background on allocating water consumption values for thermoelectric power generation, water consumption for thermoelectric generation is linked to water consumed or lost in cooling towers or reservoirs; furthermore, water consumption for the fuels required for steam generation can be traced to water consumed during the extraction and production of conventional fuels such as coal and natural gas or alternative fuels such as biomass. For renewable power generation, water consumption is traced either to evaporative losses from hydroelectric dam reservoirs and from operation and maintenance activities for plant machinery or facilities (Gleick, 1994; Merson et al, 2006; Harto et al, 2010; Fthenakis et al, 2010). Based on these water consumption components, the breakdown of water consumption for the electric grid considered for this model is shown in **Figure 35**.

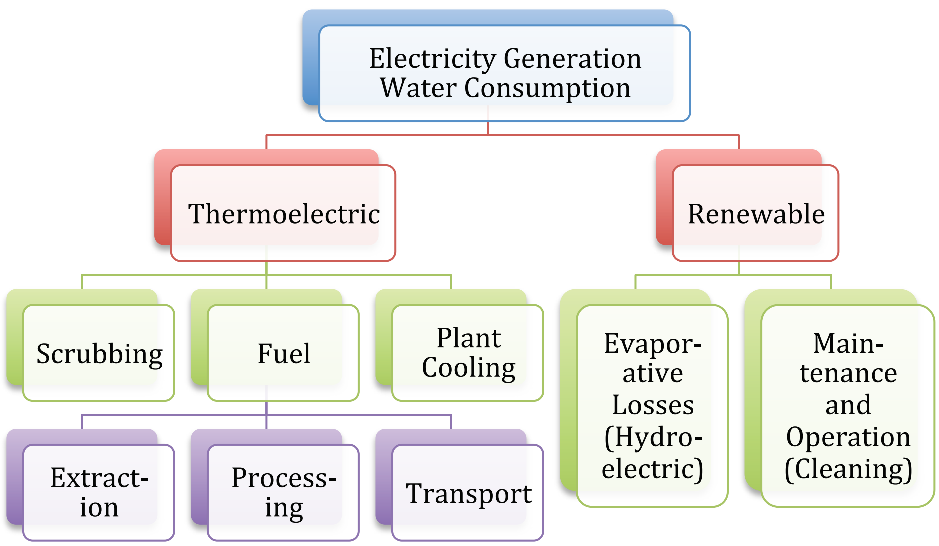


Figure 35. Electricity Generation Water Consumption Breakdown.

5.2.2.2. Fuel Infrastructure Breakdown

Existing life cycle inventories for fuel production for conventional transportation fuels such as petroleum and natural gas as well as biofuels trace water consumption to three key processes: fuel extraction from a specified source such as a well or energy crop, fuel production via processing facilities and refineries, and the distribution of these fuels via pipeline or freight transport as well as in intermediate fuel storage (Sheehan et al, 1998; Ometto et al, 2008; Harto et al, 2010; Wu et al, 2009; King and Webber, 2008 (1)). Furthermore, while some produced fuels can be transported and pumped to road vehicles without any additional processing, some fuels such as liquefied petroleum gas (LPG) and compressed natural gas (CNG) require additional processing in the form of fuel compression, where fuel can either be compressed via pressuring storage tanks with additional natural gas or fuel or via electric pumps (King and Webber, 2008 (1); Merson et al, 2006).

For renewable transportation fuels such as that of biodiesel and ethanol, fuel production components can be further decomposed into biomass crushing facilities and oil conversion plants where the feedstock is crushed to extract oil and where the oil is processed or converted into usable fuel; additionally, water consumption can also be traced to feedstock preparation such as in washing (Ometto et al, 2008; Sheehan et al, 1998). Similarly, while conventional fuels are extracted via wells or mines, renewable fuel extraction sources are traced to energy crops and associated farm inputs (Harto et al, 2010).

Based on this fuel network decomposition, a structural hierarchy for the fuel production for either conventional or alternative fuels can be described as in **Figure 36**; as with previous inventories (with the exception of the data presented in Sheehan et al (1998)), water consumption values are presented as cumulative values for each fuel network component, as summarized in **Figure 37**.

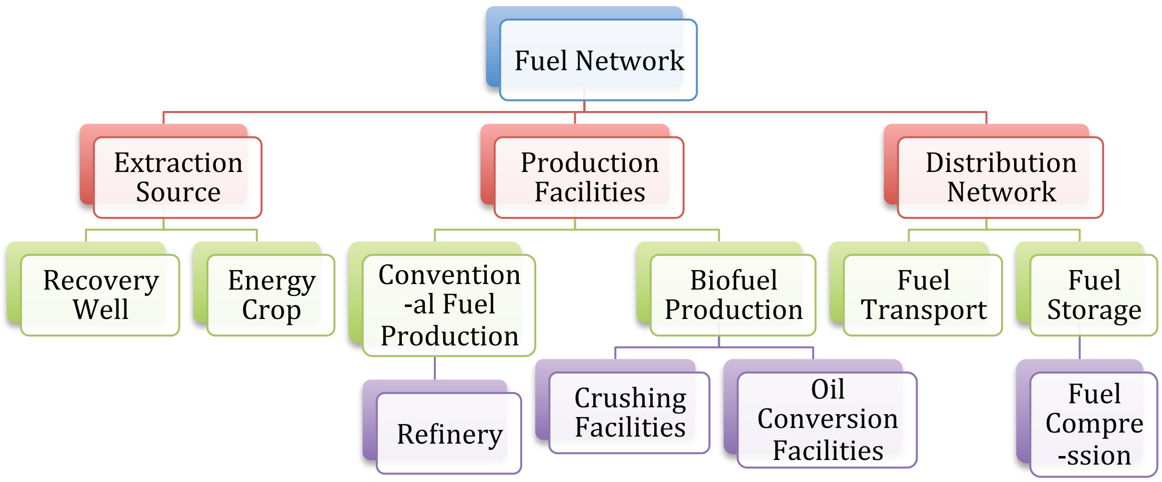


Figure 36. Structural Hierarchy of Fuel Network Infrastructure.

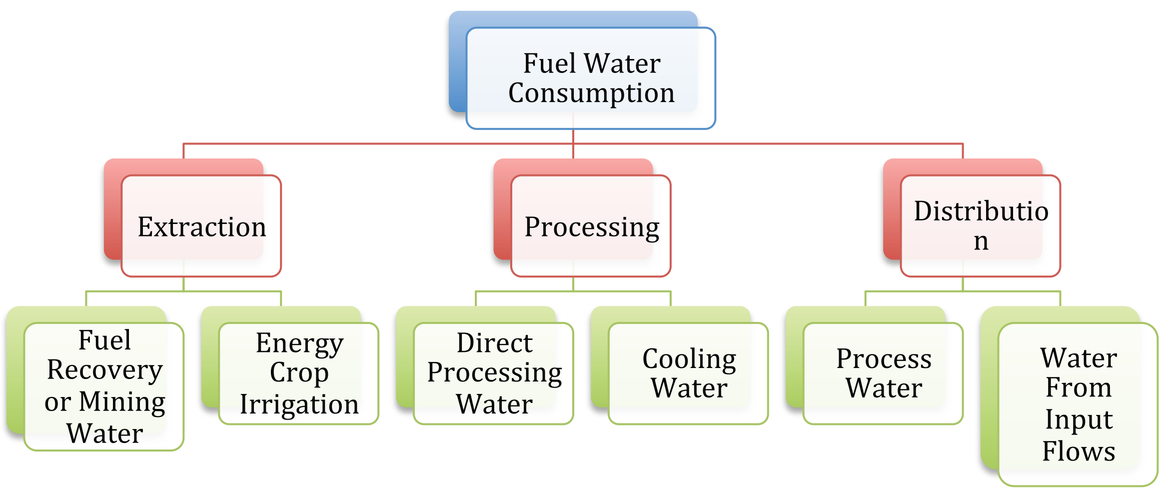


Figure 37. Water Consumption Breakdown of Fuel Water Consumption.

5.2.2.3. Road Infrastructure Breakdown

In addition to transportation modes as well as fuel and energy infrastructures in the multi-modal transportation system being considered, another set of infrastructural components to be assessed in this model pertains to the group of road networks that are required to support mobility activities within a given region. For this model, the road network hierarchy and supporting statistical data follow the definitions set forth by the Organization of Economic Co-operation and Development where a road constitutes a "line of communication using a stabilized based other than rails or air strips open to public traffic, primarily for the use of road motor vehicles running on their own wheels" (OECD, 2002). Furthermore, while road networks can encompass the roads themselves, bridges, tunnels, connectors and junctions, crossings, interchanges, and any supporting infrastructure, this model will consider only the roads and supporting structures (such as electrical components in the form of lighting systems and sensors) based on the amount of available information given between life cycle databases on road infrastructure and regional statistics on road networks (Spielmann et al, 2007; Georgia Department of Transportation, 2008).

These public roads themselves are classified under interstate freeways, supporting arterial highways and freeways, collectors that link local roads to these arterials, and local streets or in the following numerical classification shown in **Table 23** (Federal Highway Administration, 2000 (1 & 2)); similarly, road inputs for Saari et al (2007) classify roads into main arterials, collectors, and local streets (Saari et al, 2007). These breakdowns are somewhat similar to the Swiss road classifications as presented in Spielmann et al (2007), which include motorways, provincial roads, and municipal roads; an additional, numerical classification scheme is used to categorize material and energy flows for such road infrastructure.

Table 23. U.S. Road Numerical Classification (Federal Highway Administration, 2000 (2)).

Class Number	Road Description
1	Hard surface highways (Interstate and U.S. routes/highways, State routes, controlled-access highways)
2	Secondary state routes, primary county routes, municipal highway
3	Hard or loose surface roads; private industrial or residential roads
4	Unimproved local roads and driveways
5	Unimproved roads passable only with 4-wheel drive vehicles

The road network hierarchy proposed for this model is shown in **Figure 38**, where the roads considered for this model are in terms of highways or motorways, supporting arterials, and connector roads or local streets. It should be noted for this model that only paved, public roads usable by all road vehicle transportation modes in normal conditions will be considered; private roads such as industrial or residential pathways and seasonal roads are outside the scope of this model.

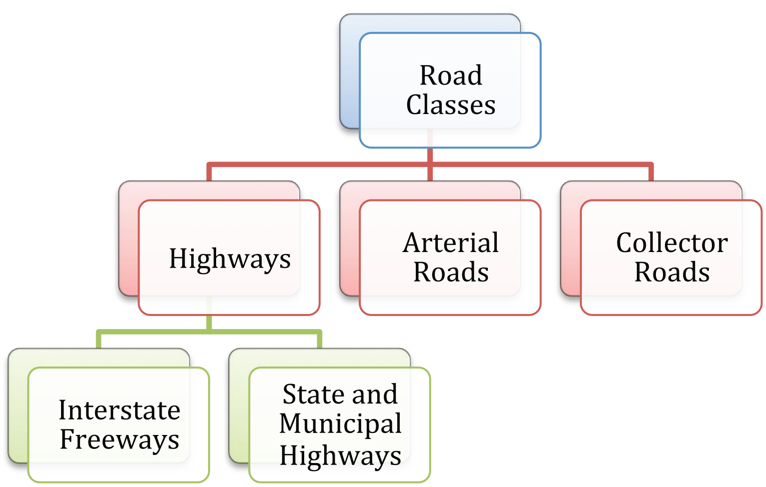


Figure 38. Road Classification Hierarchy for this Model.

Two other sets of infrastructural elements to be considered in this model are the set of dedicated equipment required for normal road operation and maintenance and the set of components pertaining to the road network's electrical systems. These inputs are based on the definition of road operation and maintenance being the set of activities required for the safe, normal use of a regional road network (Spielmann et al, 2007). In this model, electrical components for the road network being considered include lighting and illumination for each type of road, along with any traffic sensors, support equipment, and electronic signage for these roads. Additionally, the operation and maintenance equipment constitutes pavement planers, steamrollers, road rollers, dump trucks, asphalt milling machines, and other heavy equipment pertaining to maintaining existing roads.

In conforming with the system model's scope regarding assessing material, energy, and direct water flows during the use-phase of a transportation system's components, the analysis model will focus on direct or indirect water consumption stemming from water required to process material flows for road maintenance or operation (such as asphalt, gravel, and paint for road resurfacing and marking), as well as water required to produce energy inputs and expenditures for a road network's operation and maintenance infrastructure, for existing road networks. While water usage has also been traced to drainage and precipitation runoff for a transportation network's road infrastructure, this will not be considered in this model as there is no indication on how much of that water is "stored" or consumed within said infrastructure (Saari et al, 2007). Another water consumption component to be considered is the amount of water used in the production of materials required for de-icing of these roads, such as that of salt and gravel for highways and arterial roads (Spielmann et al, 2007). Other life cycle components such as land use and transformation, as well as road construction, are not considered in this model.

These water consumption components are grouped together in the hierarchy shown below in **Figure 39**. As spatially-explicit water usage data for road infrastructure is limited to that of existing studies – for example, the road network life cycle inventory discussed in Spielmann et al (2007) is based on Swiss road conditions and the material inputs for road infrastructure in Saari et al (2007) is based on Finnish road conditions – this model will assume that all of the above materials are locally procured, while equipment fuel is assumed to be procured from the current set of transportation fuels and electricity generation is assumed to be that of the regional electric grid.

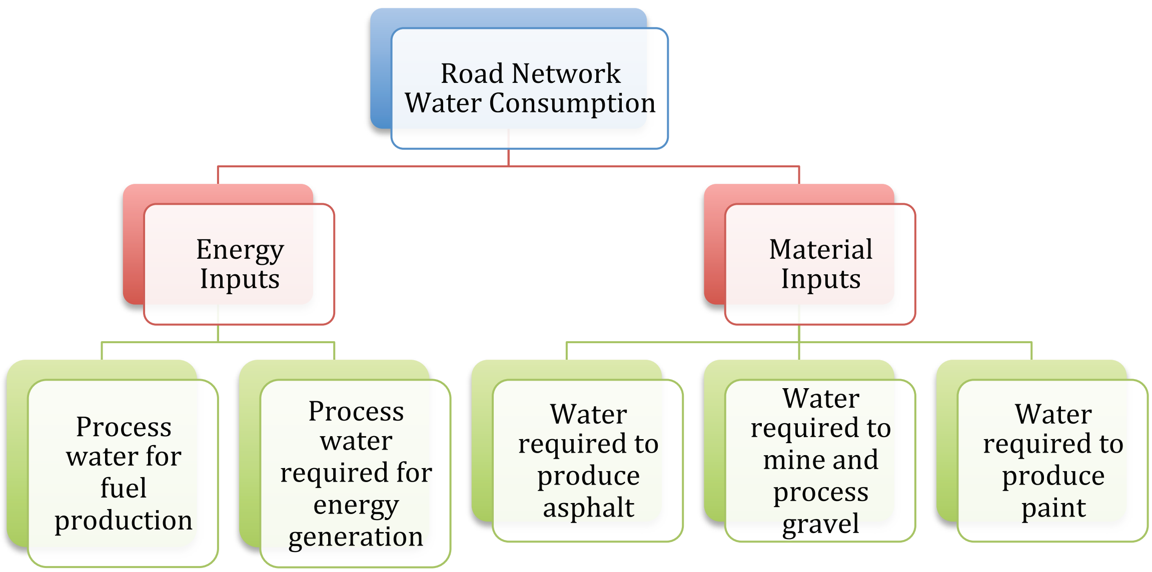


Figure 39. Water Consumption Breakdown of Road Operation and Maintenance (Adapted from Spielmann et al, 2007).

5.2.2.4. Vehicle Infrastructure Breakdown

Another infrastructural component to consider for this model pertains to the maintenance-related expenditures and inputs for the road vehicles within this transportation system. Spielmann et al (2007) includes vehicle maintenance inputs for passenger vehicles and public transportation vehicles as part of its comprehensive life cycle inventory on transport systems, where material and energy inputs assessed include grid-produced electricity, direct process water, vehicle fluids such as coolant, as well as raw materials for replacement parts and facilities construction (Spielmann et al, 2007); as with the life cycle data on road infrastructure operation and maintenance, such information is based on Swiss conditions with data sourced from life cycle assessments for a small passenger vehicle and a distribution of public transit buses and trolleybuses. While vehicle-related infrastructure for a given transportation network would also include fueling and charging stations as well as vehicle distribution and storage facilities, this model assumes that that any water and energy inputs for fueling stations are already accounted for in life cycle data regarding fuel and electricity distribution, while vehicle distribution and storage facilities are outside the scope of this model.

For this model, the service water and energy inputs are separately defined from those of the vehicle fluids that are usually replaced or added at these service facilities; as with that of road maintenance and operation, the model will examine water consumption from electricity generation as well as water consumed directly from the operation of these facilities (**Figure 40**).

Another notable water consumption component for vehicle maintenance infrastructure pertains to the water flows for carwash facilities within a transportation network. Brown (2002) examines water usage for self-service car washes, automatic washes, and conveyor car washes across all washing processes from pre-soaking and washing to rinsing and air/hand drying; a later study on car wash water usage estimates across three regions in the United States yields an average of 12.3-72.4 gallons per vehicle across all existing car wash technologies (Brown, 2002).

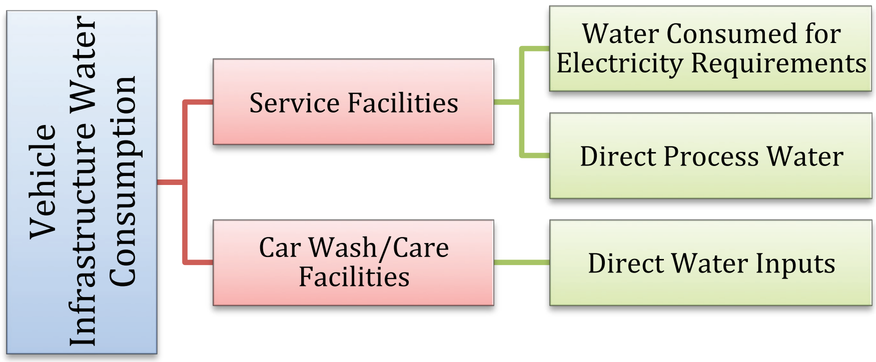


Figure 40. Water Consumption Breakdown for Network Vehicle Operation/Maintenance Infrastructure.

5.3. Defining Model Parameters and Constraints for the Transportation System Model

Based on the above breakdown of physical components of the transportation network model as well as that of water consumption inputs that are pertinent to the daily water consumption for said network, a set of quantitative parameters and associated mathematical constraints can be defined in order to integrate the performance metrics of the model's physical structure and its analytical/behavioral structure. These quantitative parameters are sourced from existing life cycle models as well as in previous assessments of measuring transportation systems performance and efficiency; although the parameters have been cited, verified, and used in numerous studies and models, the supporting constraints and mathematical expressions are not as widely disseminated, especially in reports and studies that focus on numerical results and qualitative methodology.

The following section begins with defining the pertinent metrics to be considered in this model pertaining to network performance, vehicle efficiency, and infrastructural metrics. From there, these parameters are integrated with the analysis model via a series of mathematical expressions used to calculate individual vehicle and infrastructural use-phase water consumption leading to overall daily water consumption for the transportation network.

5.3.1. Network Performance Metrics

As hinted in **Chapter 2**, urban mobility networks have generally been measured in terms of accessibility, mobility, and traffic or congestion; other measurements made for existing transportation systems have also been made in terms of energy use, land use, fuel and time costs, and material inputs (Litman, 2003; Bras, 2009; Schrank and Lomax, 2009; Saari et al, 2007). In particular, Litman (2003) defines several performance metrics for road transportation modes pertaining to accessibility, mobility, and traffic; for accessibility, metrics are based on travel time, per-trip usage, or generalized time or monetary costs.

For example, traffic measurements could be normalized in terms of vehicle-mile units, where costs or inputs are calculated based on a unit distance that a single vehicle travels – the vehicle-miles traveled metric has been used in directly comparing water consumption patterns for conventional and alternative transportation modes (Harto et al, 2010; King and Webber, 2008 (1)). Similarly, as mobility focuses on moving people and goods within an urban region, mobility measurements could be normalized in terms of passenger-miles, where measurements are based on passenger occupancy within a transportation mode across a specified unit distance; while the VMT normalization metric is useful for determining traffic trends and effects on physical vehicle types, the PMT metric is more indicative of the effectiveness of a given transportation mode (Litman, 2003; Azevedo, 2010). These metrics have also been augmented to be defined within a specified time period; for example, the Urban Mobility Report measures traffic for several metropolitan areas in the United States in terms of daily vehicle-miles of travel (DVMT) in order to account for daily traffic volumes for freeways and arterial roads and to utilize such measurements for cost calculations (Schrank and Lomax, 2009).

Other measurement definitions have been developed based on congestion and accessibility for a given transportation system. In addition to defining congestion costs and traffic-based parameters, the Urban Mobility Report includes traffic-based metrics such as average travel speed depending on congestion levels and travel delays, which are based on fluctuations in demands, bottlenecks, and unscheduled traffic incidents (Schrank and Lomax, 2009). Aggregate levels of congestion for a given network have also been represented as the Travel Time Index (TTI), which is a ratio comparing peak period travel time to uncongested travel time for a given road or entire network (Schrank and Lomax, 2009; Inrix, 2010). In terms of accessibility, a common variable used for a specific network's performance or efficiency is the daily travel distance, which represents an average commuting or driving distance within a given road network.

Most or all of the above network-specific parameters, in addition to other physical characteristics such as lane mileage (the total distance of all of the lanes within a road system) can be used in an urban mobility network in order to gauge its efficiency and level of accessibility and mobility. That said, not all underlying variables can be verified; for example, Cortright (2010) finds that traffic delays do not result in an amount of wasted fuel and level of congestion costs presented in the Urban Mobility Report. Furthermore, as all of the described measurement units are calculated based on an average of all of the passenger vehicles, trucks, and public transit vehicles used in an urban transportation system, it is important to note that performance parameters such as that of passenger-vehicle miles traveled are based on national or regional averages and do not necessarily account for variations in vehicle size or capacity, while parameters pertaining to traffic and accessibility are based on average daily travel (Schrank and Lomax, 2009). These network metrics are summarized below in **Figure 41**.

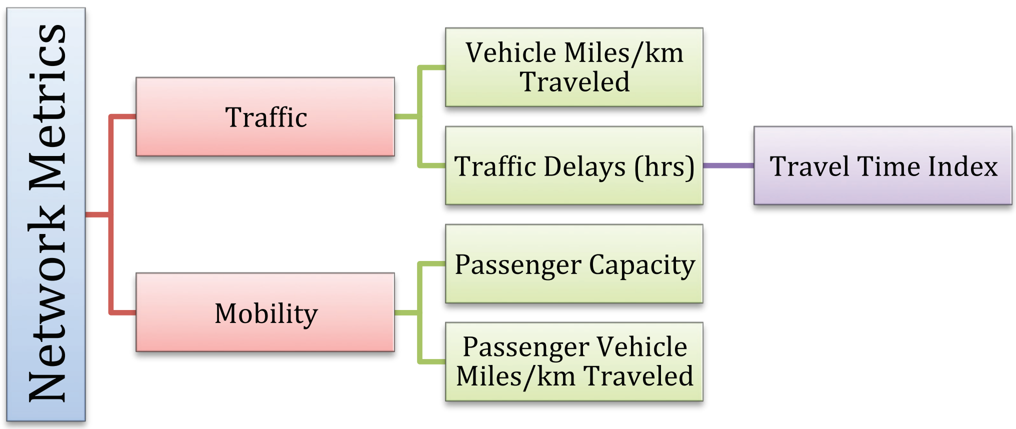


Figure 41. Summary of Applicable Network Performance Metrics.

5.3.2. Vehicle Performance Metrics

Another set of parameters that can be defined for this model pertains to the physical performance statistics of the transportation modes assessed in this transportation network. The most notable parameter to be used in the model is the fuel consumption of a given vehicle type or mode – in many existing assessments and models of various vehicle configurations, this parameter is usually represented in terms of the vehicle's fuel economy or fuel efficiency, which pertains to the tank-to-wheel fuel consumption in a given vehicle for a given unit distance. Many models such as the GREET and the Environmental Protection Agency's VISION models utilize weighted average fuel consumption parameters for a given distribution of corresponding vehicle configurations (Wang, 2010; Maples et al, 2010); on the other hand, the Urban Mobility Report accounts for fuel economy based on congested and uncongested conditions where the main driving parameter would be the travel speed in these conditions, although Cortright (2010) points out that the underlying fuel economy assumptions are not valid for current vehicle and network conditions (Cortright, 2010; Schrank and Lomax, 2009). For this model, average fuel economy values based on GREET calculations and future projections from the VISION model are used as vehicle performance parameters.

While the fuel economy/efficiency parameter can be used across all vehicle technologies using a combustible fuel as its energy source, it is only effective for these modes as it can be directly utilized in calculating the amount of fuel consumed by the vehicle's powertrain for a specific travel distance – given that water consumption for producing transportation fuels are commonly presented as volumetric ratios, using the vehicle mode's fuel economy would be appropriate as a specified volume of consumed water can be determined. For electric vehicles and vehicle incorporating electrical powertrain components, this parameter is not useful as water consumption for electricity generation is mainly presented in terms of amount of consumed water for a unit of produced energy. This is where the *energy efficiency* is used, which follows along the same premise as that of fuel efficiency but measures instead the amount of energy used by the electrical powertrain components over a specified unit distance. While the GREET and VISION models use equivalent fuel economy values for electric vehicles and PHEVs in their assessments, this metric was used instead to streamline the model's constraints, as the equivalent fuel economy parameter for electric vehicles requires a calculation of the total energy of all available thermoelectric and renewable generation sources in addition to well-to-wheel energy losses. The energy efficiency parameter has been used in King and Webber (2008) (1 & 2) in comparing electric vehicles and plug-in hybrid vehicles to biofuel and petroleum-powered vehicles, where the above measurement (in addition to accounting for powertrain component efficiencies) allows for a direct comparison of consumed water per vehicle-miles traveled (King and Webber, 2008 (1); King and Webber, 2008 (2); Campanari et al, 2010).

In addition to a vehicle's fuel or energy efficiency, there are also other parameters to consider for each vehicle type that corresponds to its use-phase water consumption, such as that of a vehicle's auxiliary fluids. As noted in the previous section, there is some water consumed in the production of a vehicle's engine coolant and lubricant, along with any hydraulic fluids; each transportation mode (passenger vehicle or bus in the case of this model) is assumed to carry the same volume of each of these fluids. That said, while some auxiliary fluids remain within a vehicle throughout its total use-phase of its life cycle and require only small additions to account for evaporative losses, some fluids such as engine lubricant are replaced from time to time over a vehicle's useful life across distance-based or time-based periods known as *service intervals* as set by vehicle manufacturers. Thus, in addition to the water intensity values for each auxiliary fluid, each also has a defined service interval, which is assumed to be the same across all passenger vehicles and the same across all bus types. These parameters are summarized in **Figure 42**.

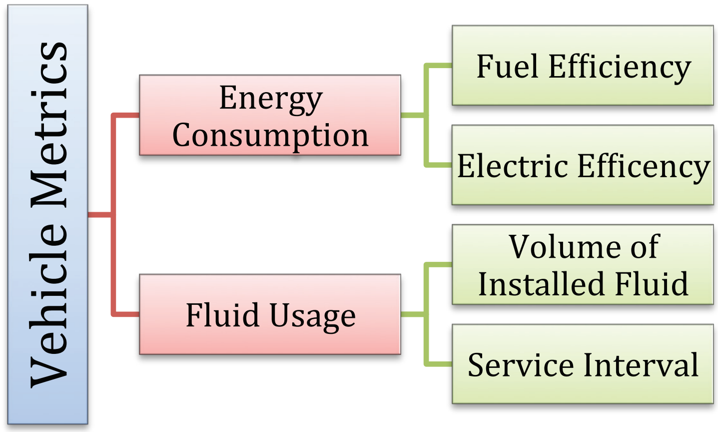


Figure 42. Summary of Applicable Vehicle Performance Metrics.

5.3.3. Parametric Constraints for the Water Consumption Analysis Model

As the analysis model for this multi-modal transportation network is primarily focused on individual vehicle use-phase water consumption and network-level consumption, a set of parametric constraints needs to be defined in order to integrate the life cycle data presented in Chapter 3 with the network and vehicle-based parameters specified in the previous two sections. Based on the above problem formulation and presented data, a mathematical model can be developed based on previous research in allocating water consumption for various transportation modes as well as that for their supporting infrastructure. The following sub-sections detail key top-level water consumption calculations for this model; more detailed mathematical expressions for calculating individual water consumption components can be found in **Appendix A.1**.

The total water consumption for the use-phase of each vehicle (with the exception of water consumed in the vehicle's corresponding service and washing facilities) is the previously defined use-phase water consumption for each vehicle configuration added with the water consumption. This is multiplied with the daily driving distance that is specific to the urban region being considered in order to determine the total estimated use-phase water consumed per day (d_{daily}, in liters per day) as expressed in **Equation 1**.

$$V_{usePhase}(water)\ [l/day] = \left(W_{WTW,use} + W_{fluid}\right) * d_{daily} \quad (1)$$

Based on the above equations, the total water consumption traced to material, energy, and water inputs for all considered transportation modes in this model is the sum of the products of the well-to-wheel water consumption components and their associated vehicle market share percentages *n*; these values are multiplied by the total number of vehicles for each fleet of automobiles or buses *X*. Cumulative use-phase water consumption for these vehicles is broken down into water consumption traced to automobile usage and water consumption for bus usage. For either fleet of transportation modes, the total water consumption traced vehicle usage, for a given day, is shown below in **Equation 2**.

$$V_{fleetUsage} = \sum_{i=1}^{m} X_{fleet} * [n_{vehicleMode} * V_{usePhase}(water)] \quad (2)$$

In addition to vehicle usage, vehicle servicing infrastructure water consumption for an entire fleet of automobiles or buses can be estimated by multiplying individual service water consumption inputs with the number of vehicles in each fleets. While this is not necessarily an accurate approximation of actual water consumption in vehicle servicing facilities as these inputs are associated with a single vehicle and not to an actual facility, the expression detailed in **Equation 3** is intended mainly to serve as a "placeholder" in assessing top-level infrastructural usage water consumption. A breakdown of service water consumption inputs can be found in **Appendix A.1.4.**

$$V_{fleetServicing} = \sum_{i=1}^{m} X_{fleet} * [V_{servicing} + V_{washing}] \quad (3)$$

As discussed in **Section 5.2.2.3**, overall water consumption for each type of road within a mobility network in terms of its use-phase can be divided into water required to produce the necessary raw materials for road resurfacing, repainting, and de-icing as well as water consumed to produce the energy required for operating the road's electrical components and maintenance equipment (Spielmann et al, 2007); based on this breakdown, water consumption for each road can be estimated by summing these indirect water inputs as shown in **Equation 4**. Individual water consumption factors for each kilometer of road are described in detail in **Appendix A.1.4**. At this time, the water consumption for each road is per kilometer of road; furthermore, the amount of material and energy inputs varies across highways, arterials, and collector roads/streets. The water consumption associated with each of these roads are combined with their respective amount of road lane mileage for the transportation system being considered to estimate the overall annual water consumption traced to a mobility network's roads and supporting infrastructure (**Equation 5**).

$$W_{road}[\,l/km] = \left[\sum_{i=1}^{n} (W_{roadMaterial,i})\right] + W_{roadEquipmentFuel} + W_{roadElectricity} \quad (4)$$

$$V_{roadNetwork}\,[l/day] = [W_{road}(highways) * d_{highways}] + [W_{road}(arterials) * d_{arterials}] + [W_{road}(collector) * d_{collectors}] \quad (5)$$

Ultimately, these top-level water consumption values are added together to estimate the total daily water consumption for a transportation network encompassing these vehicles and supporting infrastructure, as shown in **Equation 6**.

$$V_{total} = V_{automobileFleet} + V_{autoServicing} + V_{busFleet} + V_{busServicing} + V_{roadNetwork} \tag{6}$$

While the calculation of fuel production and electricity generation water consumption is an integral component of this model, these components are themselves not allocated to total infrastructural water consumption. Instead, these calculations are "embedded" in individual vehicle mode and road/vehicle infrastructure analyses, as these are flows that are ultimately consumed by this transportation system. The mathematical framework for calculating total and average water consumption for a region's electric grid or fuel production pathways is described in **Appendices A.1.2 and A.1.3.**

5.4. Developing the SysML Model

Based on all of the above parameters and constraints defined as well as the subdomain hierarchies proposed in **Section 5.2**, a system model is developed using SysML using MBSE principles and portions of the Vee Model discussed in the Approach and Methodology of this thesis. The next subsections introduce the model hierarchy and packaging along with the model domain's components, from where the initial requirements of the model and the system being considered are defined. Based on the requirements and the material input pathways discussed in Chapter 3 for each vehicle type, physical allocations and component functions/activities can be defined, from which the physical structure of the vehicles, road and vehicle infrastructure, and energy/fuel pathways can be specified. As the model is focused on determining network-wide water consumption for vehicle and infrastructure usage, a top-level analysis context is defined pertaining to integrating water consumption and performance parameters with associated mathematical constraints, from which the model is executed using ParaMagic and Mathematica for several defined scenarios.

5.4.1. Defining the System Package Hierarchy

The hierarchical structure of the SysML is based on a series of directories and sub-directories called **packages,** which are defined based on structural components, parametric elements, defined functions or activities, requirements, and material flows. The package hierarchy is shown below in **Figure 43.**

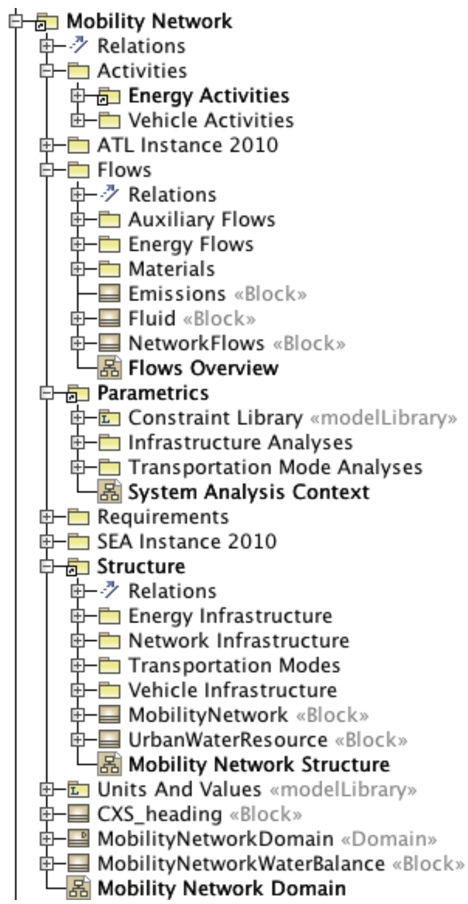


Figure 43. SysML Model Package Hierarchy.

Another viewpoint of the system model hierarchy can be represented in SysML as a series of **package diagrams**, from which the folders and subfolders can be represented graphically along with associated relationships called **containment** connections linking a child package or library to its parent folders. In this model, the top-level package **Mobility Network** pertains to the system of interest where components such as vehicle modes and infrastructure are contained within the **Structure** package, while analysis elements are placed under **Parametrics**. Similarly, the requirements for the model are divided into system-level requirements and modeling requirements; these are placed under **Requirements.** Other packages exist for storing value types and units required for the analysis model, in addition to definitions of material and energy flows for the domain of interest and functions or physical flow descriptions for the transportation network being considered. This package diagram is shown below in **Figure 44** along with associated containment relationships.

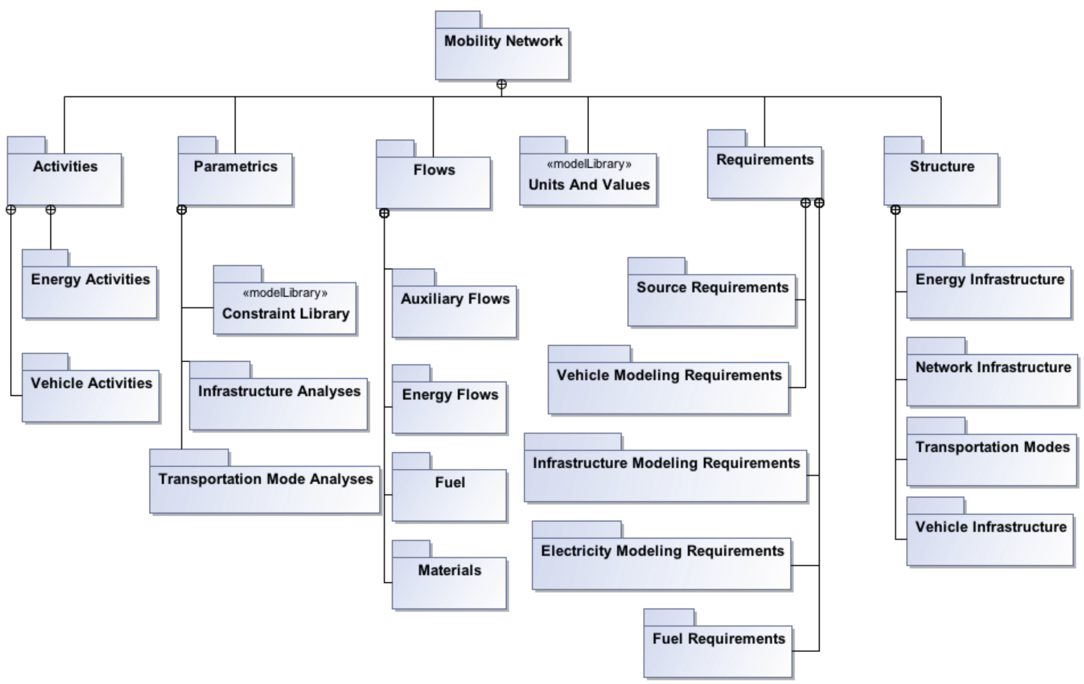


Figure 44. SysML Package Diagram of Mobility Network System.

As discussed in the Approach and Methodology chapter, the system boundary for use-phase water consumption within an urban mobility network needs to be properly defined and constrained as a mobility network can potentially contain several transportation modes and supporting components along with additional material flows. Thus, the first step in the development of this model is to specify the top-level and component requirements detailing how the model and its structural and analytical objects should be specified and scoped and to specify the domain of interest and the objects or items to be assessed in this system.

5.4.2. Specifying the Requirements for the Model

The first step in developing any system or design as specified in systems engineering and systematic engineering design processes is to form a series of multidisciplinary requirements that would need to be satisfied or achieved during the development and execution of the system model or design. One of the capabilities within the Unified Modeling Language and SysML is the ability to define requirements and constraints from top-level scope requirements or problem statements to component-level constraints and performance specifications. These requirements, which are either qualitative or quantitative, are stored in **requirements blocks** where these objects can be leveraged, allocated, or reused to structural or behavioral constructs within the model.

In this model, the requirements are created mainly to ensure that the system scope specified in **Chapter 3** has been properly implemented, along with requiring which components to be assessed within this model. Additionally, some of the system-level constraints and boundaries can be specified as design constraints or requirements on the top level or at the component level. The next few sections will describe some of the requirements specified in the mobility network system analysis model, where these requirements can displayed in **requirements diagrams, requirements tables,** or

requirements matrices. The hierarchy for the requirements defined in this system model is shown in **Figure 45**.

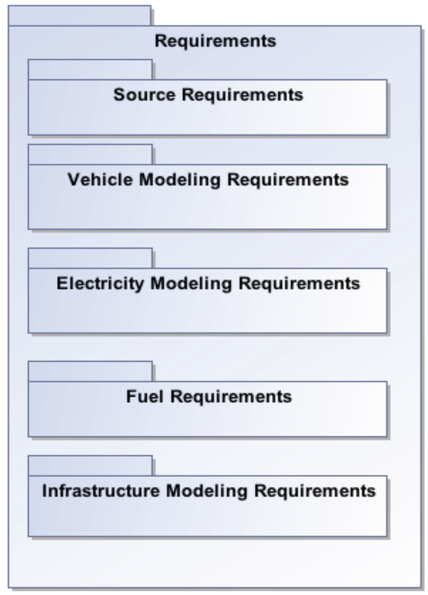


Figure 45. Model Requirements Breakdown in the SysMl Model.

5.4.2.1. System-Level Requirements

The core of the research questions presented in this thesis is to determine the overall water consumption for a specified urban mobility network's transportation modes and infrastructure, from which it was proposed that a SysML model can be constructed in order to help provide answers to this question. Based on these questions, the top-level, source requirement for this model is to develop a structural and analysis model of an urban transportation system that would incorporate MBSE principles and object-oriented modeling components with the intention of analyzing the overall water consumption resulting from the use-phase of the system's associated components. This requirement, stored in a block labeled **System Model Requirement**, is shown below in **Figure 46**.

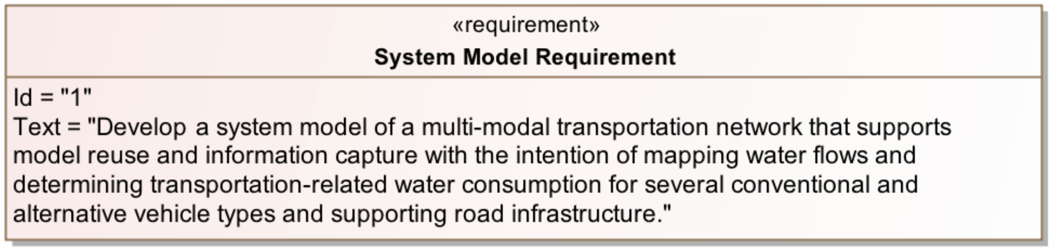
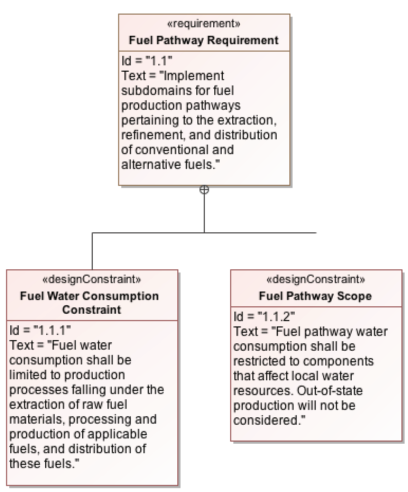
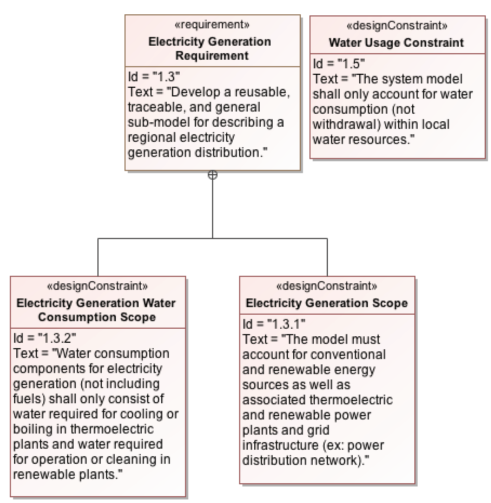


Figure 46. System Requirement Specified in SysML.

Based on this top-level requirement, a series of sub-requirements can be specified pertaining to developing and scoping model sub-domains and objects pertaining to the network's road and energy infrastructures as well as for modeling the vehicles within this network. For example, based off of the system requirement, a **Fuel Pathway Requirement** can be defined in which the requirement demands that subdomains for fuel pathways pertaining to fuel extraction, production, and distribution for conventional and alternative transportation fuel be implemented in this model (**Figure 47**). Similarly, a sub-requirement for the electricity network sub-domain as well as for stipulating that water consumption be limited to local material, energy, and water inputs can be defined in this model (**Figure 48**).





LEFT: Figure 47. Fuel Network Requirements Contained in System Requirement.
RIGHT: Figure 48. Electricity Network and Water Consumption Scope Requirements.

A full description of system requirements as well as a breakdown of lower-level requirements such as for energy pathway and vehicle modeling can be found in **Appendix A.2.**

Ultimately, these requirements will serve as regulations and constraints for the analysis model to be developed within SysML, where each of these requirements can be related to one or more structural or parametric elements within the system model using crosscutting relationships known as **allocations**. For example, a set of structural blocks defining an IC-powered vehicle would need meet the requirements stated in this section of the model; in SysML, this relationship can be defined as saying that these blocks *satisfy* the requirements being considered and are represented by a <<satisfy>> allocation connector from the structural or parametric block to its source requirement (Friedenthal et al, 2008), as demonstrated in **Figure 49**. Such allocations will be utilized when validating the model's structure in **Chapter 8**.

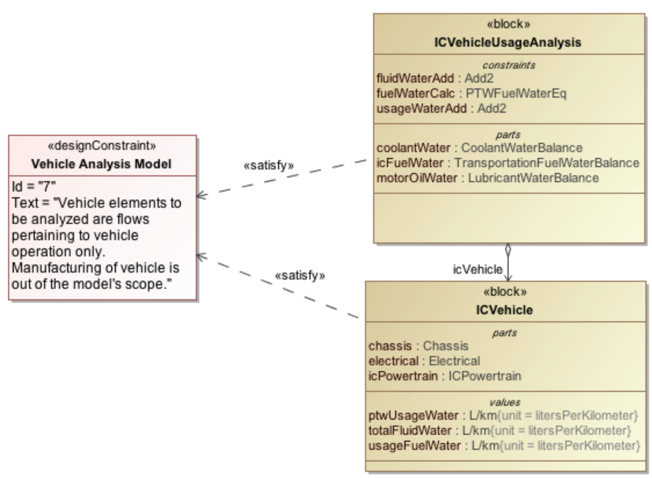


Figure 49. An Example of Cross-Cutting Relationship (<<satisfy>>) in SysML.

5.4.3. Developing the Transportation Network Domain

The next step in developing the model is to specify the domain of the urban mobility network to be assessed in terms of water consumption. In the previous chapters and sections, it was observed and determined that water consumption can be traced to the direct water usage and material and energy flows consumed within this transportation system and its physical components. Based on these observations, a system domain was implemented in the SysML model that includes the **MobilityNetwork** structure itself in addition to the flows being considered (represented by the **NetworkFlows** block and referenced or contained blocks representing the specific material and energy flows within this system. Additionally, the domain to be considered includes a block representing the local freshwater resources, which are assumed to be the source of all water flows into the material and energy sources as well as to the transportation modes and infrastructure themselves, as shown in **Figure 50**. The following sections will focus on the structural breakdown of the **MobilityNetwork** block; a detailed breakdown of network flows will be discussed in **Appendix A.3.1.** Activities and physical allocations associated to vehicles and infrastructure in the transportation network have already been discussed in the Background and Literature Review as well as in the proposed model structure of this thesis; these elements have been placed in **Appendices A.3.2. and A.3.3.**

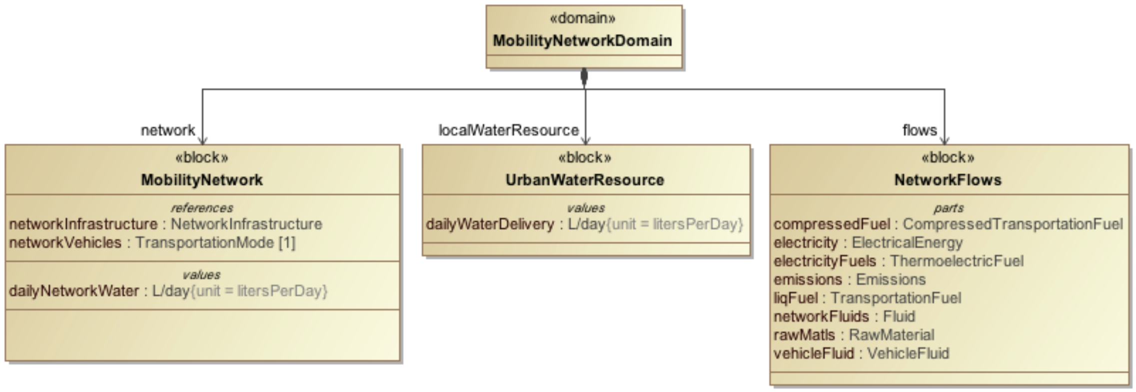


Figure 50. System Domain Specified in SysML.

5.4.4. Top-Level Structural Breakdown of System Transportation Modes and Infrastructure

The next major component in the domain of this system model pertains to the structural breakdown of the road transportation modes and associated infrastructure for this multi-modal transportation network. The overall structure for this portion of the model is summarized below in **Figure 51**.

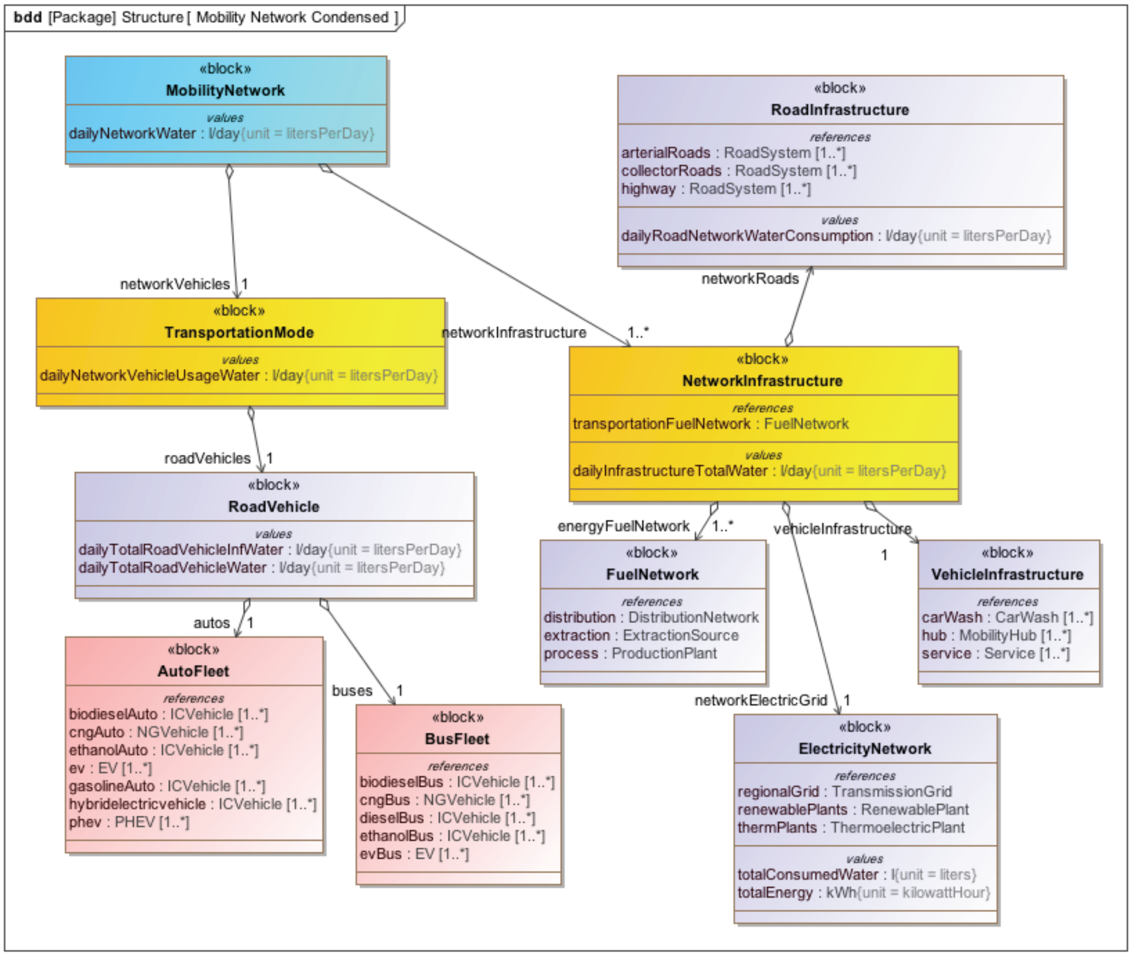


Figure 51. Block Definition Diagram of Structural Breakdown in SysML Model.

As with the hypothetical structure presented in Section 5.2, the mobility network structure is divided into applicable transportation modes as well as for associated infrastructure; the **TransportationMode** block itself references the set of road vehicles being considered, while the **NetworkInfrastructure** block references the fuel pathways to be assessed in this model, road infrastructure, vehicle servicing infrastructure, and the electric grid for this transportation system. The road vehicles themselves are divided into automobiles and buses, where the vehicle propulsion technologies are represented as reference properties for each type of vehicle. As mentioned in the vehicle mode breakdown of conventional and alternative fuels/configurations, these vehicle types are separated structurally as the use-phase water consumption for certain vehicle types are calculated differently or they may have different material inputs. At this level, both automobiles and buses have equivalent vehicle components such as powertrain and chassis elements, with separate parameters pertaining to material inputs and fuel consumption; as such, both the Auto and Bus blocks reference vehicles of the same propulsion configurations.

For each of the top-level blocks, the key value properties stored in each object pertains to the daily water consumption traced to its components, from where water consumption value properties from each of the lower-level structural blocks can be connected to constraints within the analysis-focused section of the model, which will be discussed in a later section. Additionally, each vehicle or infrastructure element (such as for **ICVehicle** and for **RoadSystem**) contains performance physical parameters pertaining to efficiency such as for fuel consumption and component efficiencies and physical parameters such as road lane mileage.

It should be noted that the top-level structural blocks (down to the **Auto, Bus,** and other cumulative infrastructure blocks) are not physical objects or elements within a network; rather, they serve as sub-systems and sub-domains from which each aggregates more tangible elements within the network such as individual vehicles, roads, plants, and specific infrastructure or materials – hence, the aggregate association connections among these blocks as represented as a white diamond from the source block one end and an arrow connected to the associate block.

5.4.4.1. Structural Definition of Vehicle Types

The first major subset of the structure to be discussed in this model is the set of vehicle types organized by propulsion technology as shown in its associated package overview in **Figure 52**. Each vehicle type specified in the model requirements as well as in the proposed structural hierarchy shown earlier in this chapter is specified as a block, from which the physical breakdown of each vehicle type can be represented as a series of composite associations. As previously discussed, an abstract breakdown of a vehicle's physical components include its chassis, powertrain, electrical system, interior, wheels, drivetrain components, and many more. For this model, these vehicle types were divided primarily based on how water consumption for each vehicle's use-phase inputs would be calculated; for example, while natural gas vehicles (NGVs) use internal combustion powertrain components, they store fuel differently and require compression or liquefaction of natural gas before the fuel can actually be used for these modes; thus, it is separately defined as **NGVehicle**. On the other hand, as electric vehicles have significantly different powertrain components such as battery packs and electric motors, in addition to the dissimilar calculation of normalized water consumption from electricity generation, EVs are defined separately under a block named **EV.**

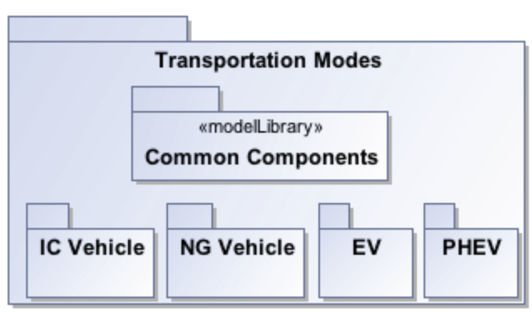


Figure 52. Package Overview of Transportation Modes in SysML Model.

However, all of these vehicles share a series of common components – for example, as electric vehicles are mostly based off of IC vehicle platforms at this time, they would most likely share chassis and wheel assembly components. Similarly, it is assumed that all vehicle types being considered for either automobiles or buses share similar electrical components. As the transportation modes are defined as abstractions of actual vehicle configurations, the common components assumption can be extended to fuel storage tanks for both gasoline/biofuel and natural gas vehicles or for electric powertrains for plug-in hybrid vehicles, although actual configurations for these elements across either vehicle type would be significantly different. Ultimately, the intent of implementing common components across these transportation mode representations is to apply model reuse and object-oriented modeling to the vehicles being considered in this system so that blocks or properties that are similar across multiple configurations can be leveraged for each of these variations. In this model, these common vehicle components and subsystem blocks are stored in specialized packages called *model libraries* where these parts can be referenced or associated to multiple vehicle configurations (**Figure 53**). Variations in parameters or properties for each of these common components can be addressed in **instances** where vehicle types and configurations can be defined more specifically; these instance specifications will be discussed in a later section.

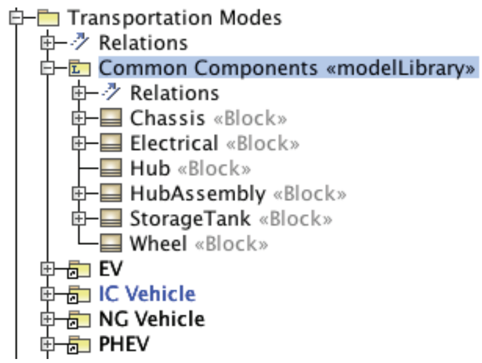


Figure 53. Common Components Stored in Model Libraries within SysML.

These generic components are used in conjunction with more bespoke elements such as IC powertrains and electric motors to constitute vehicle type representations in the SysML model. The first main vehicle type to be specified is the group of gasoline and biofuel-powered vehicles represented as the **ICVehicle** block, as shown in **Figure 54**. The top-level vehicle block includes part properties (represented as composite associations in the model) pertaining to the vehicle's powertrain subsystem (which is itself composed of the vehicle's engine), electrical components, and the vehicle's chassis and associated wheel assemblies. Additionally, the IC vehicle's powertrain references the fuel being used (**TransportationFuel)** and other fluid flows that are present in this vehicle type. For vehicle types that use compressed natural gas, a separate **NGVehicle** is defined that uses the same structural breakdown, albeit with a different fuel **CompressedTransportationFuel**. To differentiate the compressed-fuel powertrain system in NGVs from powertrains present in vehicles using petroleum-based fuels and biofuels, a separate powertrain NGPowertrain is defined in the NGVehicle structure; however, as the overall performance parameters for each powertrain is the same, the NGPowertrain block is defined as a specialization of the ICPowertrain block (**Figure 55**).

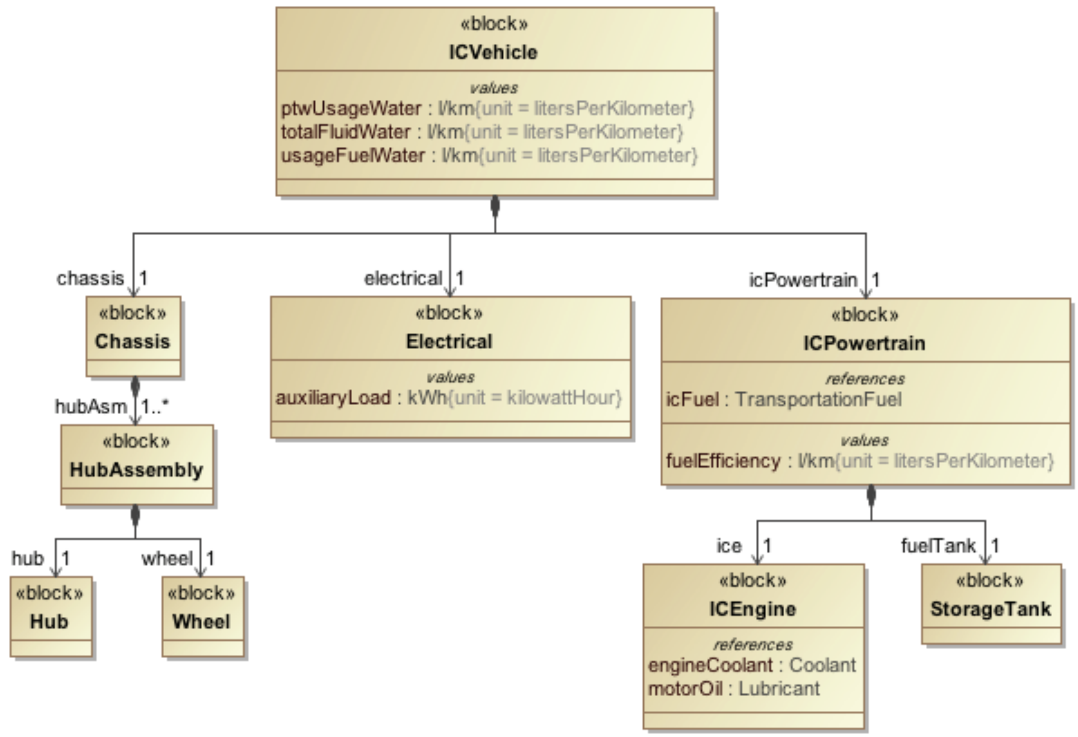


Figure 54. IC Vehicle Structural Breakdown.

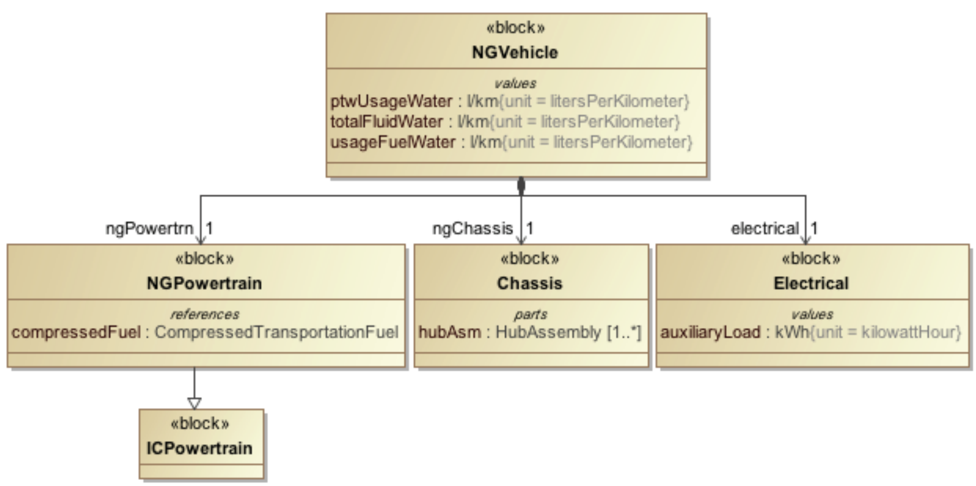


Figure 55. NG Vehicle Structural Breakdown with NG Powertrain Specialization.

Electric vehicles are similarly defined where a top-level block called **EV** contains part properties pertaining to the vehicles' chassis, powertrain, and electrical components with blocks specifically defined for electric vehicles (such as **EVPowertrain**) and blocks reused from the Common Components model library; the breakdown for this vehicle type is shown in **Figure 56**. The EVPowertrain block itself consists of an electric battery pack (listed as **Battery**) and motor; both components also consist of value properties representing efficiency values (such as the charging and discharging efficiencies for the battery and performance efficiency of the motor) or other operating parameters such as battery energy output. As with the internal combustion engine, the electric vehicle's powertrain uses electricity generated from the local electric grid; thus, a reference association is implemented between the powertrain and the associated electrical energy flow. As the battery requires coolant for normal operation, a reference association is also defined between the battery and associated coolant flow.

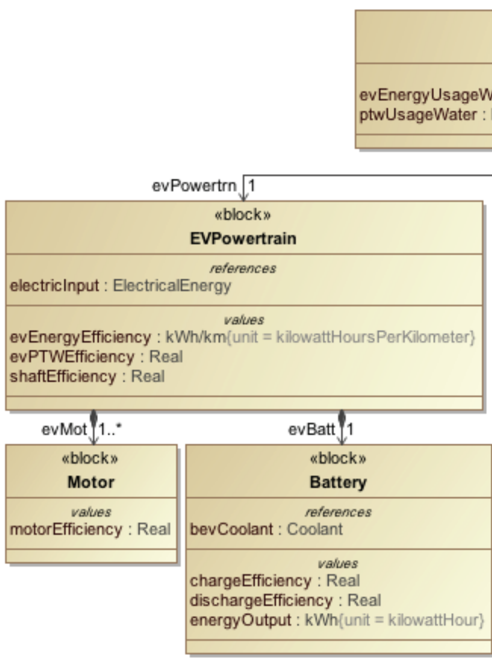


Figure 56. EV Physical Breakdown in SysML Model.

The next unique vehicle structure defined in this model pertains to that of plug-in hybrid vehicles (PHEVs) – in contrast to the above two configurations where the powertrain subsystem consists either of only IC-based components or electrical propulsion elements, PHEVs utilize both sets of powertrain components for normal operation; in this model, it is assumed that the powertrain for PHEVs consist of an IC powertrain and EV powertrain, with both powertrains leveraged from the above two structural compositions. In terms of structural definition, the PHEV block only differs from either IC or EV vehicle structural definitions in that the PHEV block has part properties for both the EV powertrain and IC powertrain subsystems.

5.4.4.2. Structural Definition of Energy Infrastructure

Another key subdomain of the mobility network structural breakdown is that of the electricity generation network, which consists of the power plants and associated energy sources that are needed to generate electricity as well as the transmission grid needed to distribute such electricity to the urban mobility network. This electricity infrastructure is represented within the **ElectricityNetwork** block as shown in **Figure 57**.

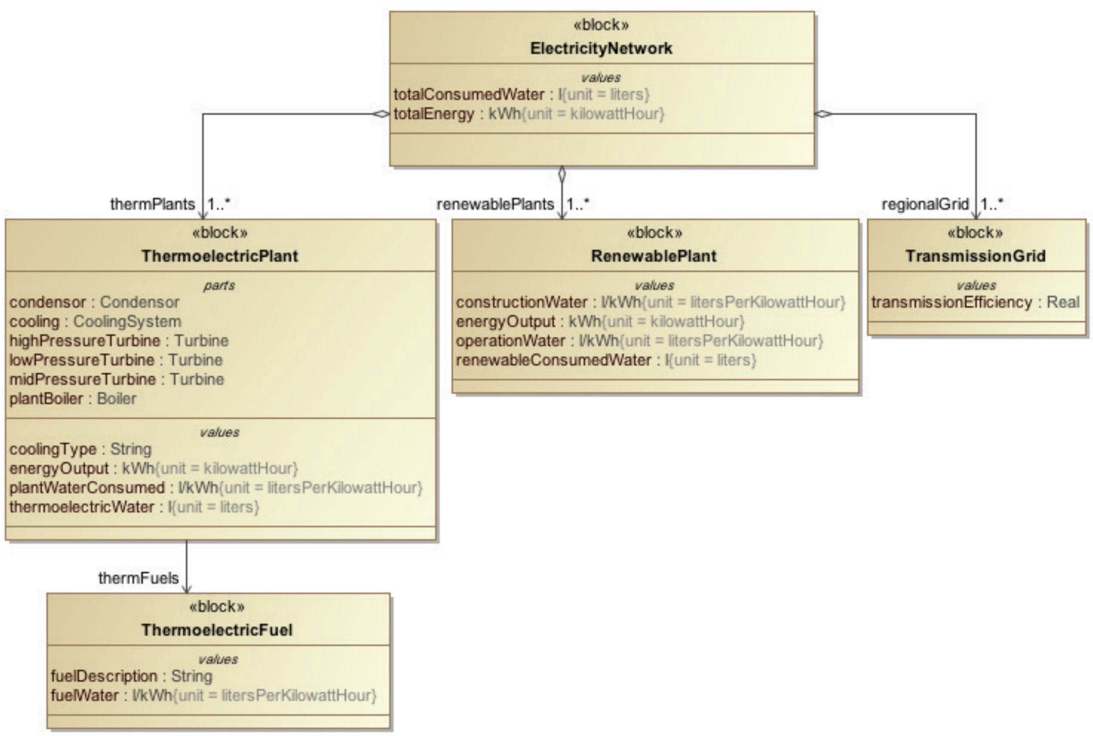


Figure 57. Electricity Network Infrastructure Breakdown.

The electricity network sub-domain references two types of generation methods – thermoelectric and renewable plants – along with the associated distribution system. Each generation type also contains a series of value properties pertaining to generation type, the amount of energy output, plant-related water consumption values, as well as the aggregate amount of water consumed for each group of energy sources. Additionally, the ThermoelectricPlant can be further defined to include part properties pertaining to the cooling system, boiler, and steam turbines to be utilized in specifying the material and water flows for these plants as shown in **Appendix A.3.3.2**. Furthermore, each thermoelectric plant in the transportation network has an associated fuel or energy source; in the SysML model, the **ThermoelectricPlant object references the ThermoelectricFuel** block. The ThermoelectricFuel block has a similar set of value properties to that of the TransportationFuel block; these energy flows will be discussed in further detail in **Appendix A.3.1**.

Another energy infrastructure sub-domain included in this model pertains to the fuel production network required to produce and/or distribute the transportation and thermoelectric energy fuels for this multi-modal transportation system. The physical elements required for fuel production are defined under the sub-domain block **FuelNetwork** in **Figure 58** where the network aggregates the extraction sources, production or processing plants, and the distribution network for these fuels, based on the structural hierarchy and water consumption breakdown shown in **Section 5.2**.

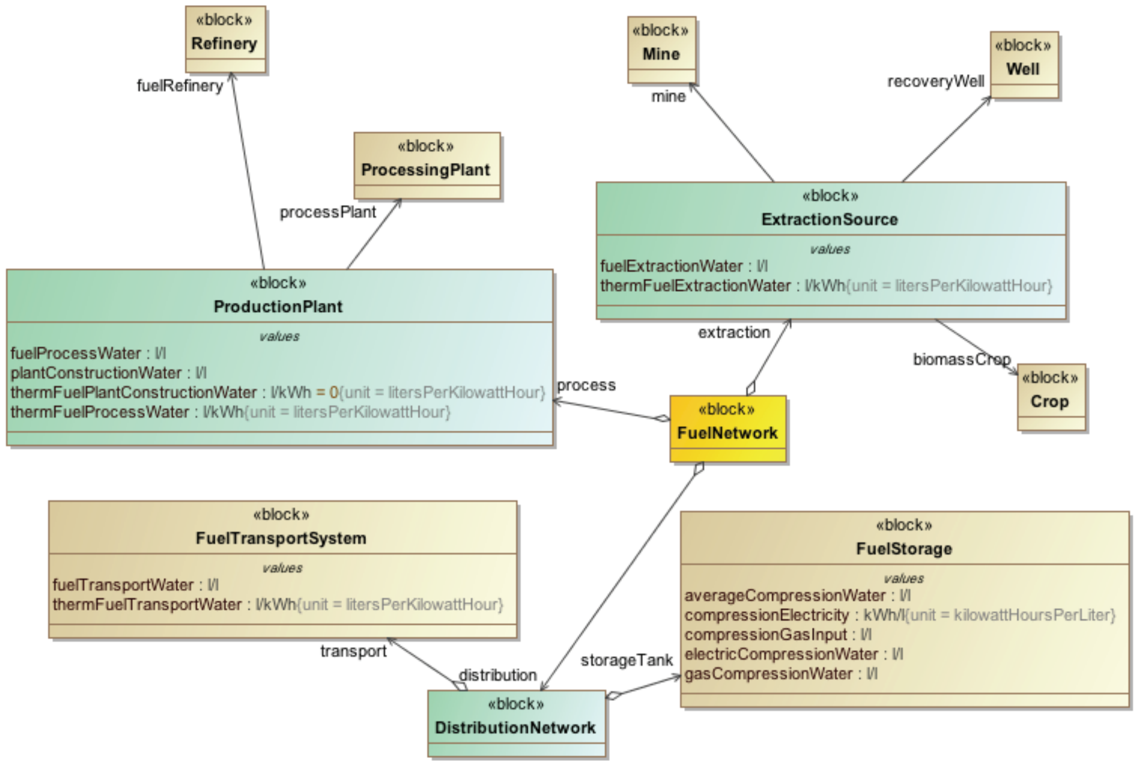


Figure 58. Fuel Network Definition in SysML Model.

These three blocks themselves are composed of more fuel-specific production components such as refineries for petroleum gasoline and processing plants for biofuels for the set of production facilities as well as wells or energy crops for the set of extraction sources. The fuel distribution network as described in **DistributionNetwork** aggregates the transport components as well as fuel storage elements. The ExtractionSource and ProductionPlant blocks contain value properties pertaining to water consumption components for each stage of the fuel production process – for the extraction source definition a parameter pertaining to the water consumed in extracting raw fuel materials is defined, and for the production plant water consumption values for fuel processing and facility construction are included. In particular, the fuel distribution network components have water consumption parameters defined separately, as for fuel storage water consumption is more significant in the compression or liquefaction of gases such as natural gas; on the other hand, the water consumption traced to fuel transportation is defined within the FuelTransportSystem block. As the normalized water consumption for electricity generation and water consumption for transportation fuels are determined differently using different units, thermoelectric fuel-related water consumption is separately defined, as the fuel network structure is also relevant for the production and distribution of thermoelectric fuels.

5.4.4.3. Road Infrastructure Definition

The road network for the transportation system in this model is defined as a separate sub-domain consisting of separate reference properties of road infrastructure packages defined by the **RoadSystem** block; these properties correspond to the road classifications being considered in this mode – highways and interstate freeways, connector roads such as boulevards and minor arterials, and local streets as shown in **Figure 59**. The RoadSystem block itself comprises of relevant infrastructural components being assessed in terms of water consumption; in this model, the components defined include the physical road itself (represented as **RoadSurface**), electrical subsystems including road lighting systems and electronic signage or sensors, as well as other infrastructural components such as that of maintenance equipment, tunnels, bridges, or other auxiliary elements. In addition to defining the physical infrastructure aggregated into these individual road types, material and energy flows that are required for the use-phase of these roads – for the roads' electrical components, the electricity produced by the local electricity grid is referenced, while transportation fuels are referenced by the operational and maintenance equipment for this infrastructure sub-domain (**Figure 60**).

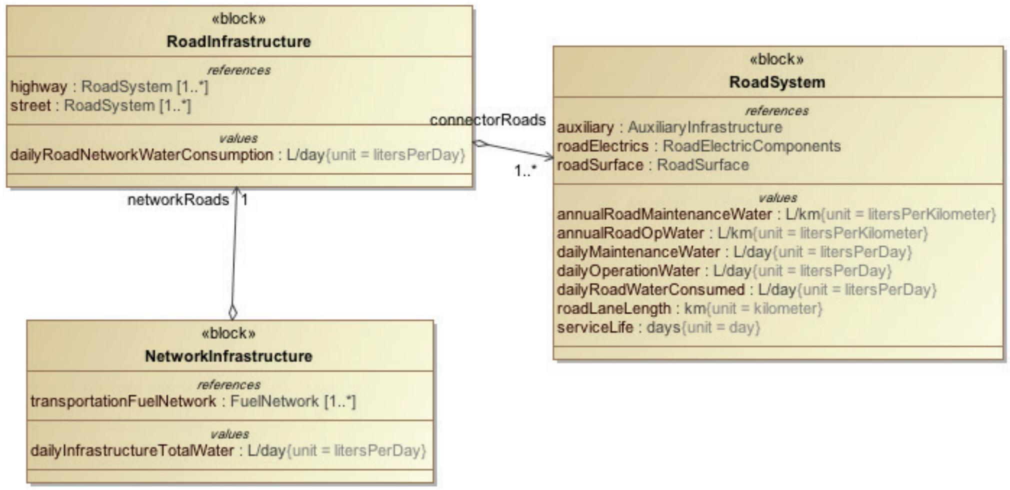


Figure 59. Road Infrastructure Sub-domain Definition in SysML Model.

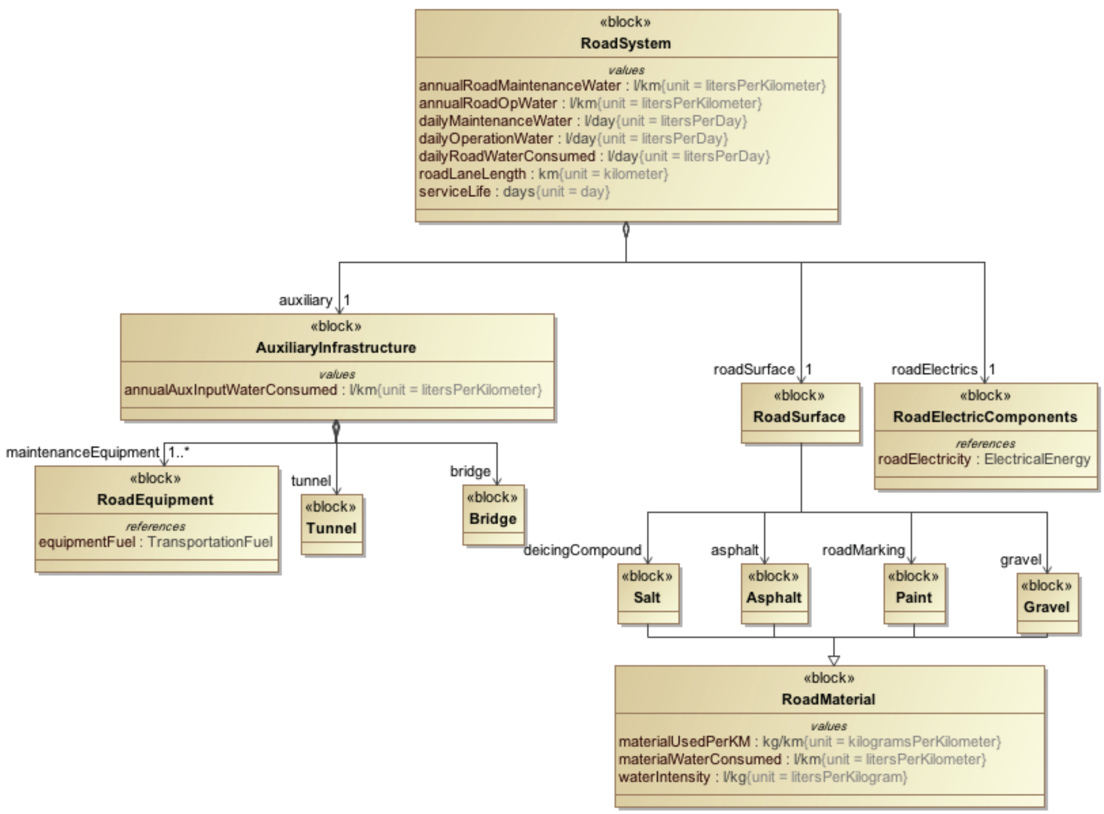


Figure 60. Individual Road Type Structure Breakdown.

Other life cycle use-phase flows such as materials required for road maintenance or operation activities such as that of asphalt and gravel for resurfacing and salt for deicing are associated to the **RoadSurface** block as reference properties; each specified material contains water intensity parameters inherited from the generic flow block **RoadMaterial** which is specified as part of the transportation network's flows. These individual water consumption components as well as material consumption parameters (such as that of electricity and fuel consumption) are integrated with aggregate use-phase direct/indirect water consumption parameters within dedicated analysis blocks as with those of the transportation modes discussed earlier.

5.4.4.4. Vehicle Infrastructure Structure Definition

The last infrastructural sub-domain to be discussed in this SysML model pertains to the vehicle service infrastructure that encompasses the network of maintenance facilities for both automobiles and buses along with a corresponding network of washing facilities as discussed in Spielmann et al (2007) and Brown (2002). These two facilities are defined as blocks that are aggregated to the sub-domain block **VehicleInfrastructure** as shown in **Figure 61**. Water consumption parameters pertaining to direct water or energy flows are defined as value properties and are integrated within the corresponding water balance analysis for said infrastructure; for vehicle servicing, the key value properties include annual electricity consumption and annual direct water usage; similarly, for car wash facilities the key water consumption parameter pertains to the direct water consumed for each washing operation and for each vehicle. As discussed in the hypothetical water consumption breakdown for vehicle infrastructure, the water consumption is normalized to a daily basis given an estimated time interval between washes.

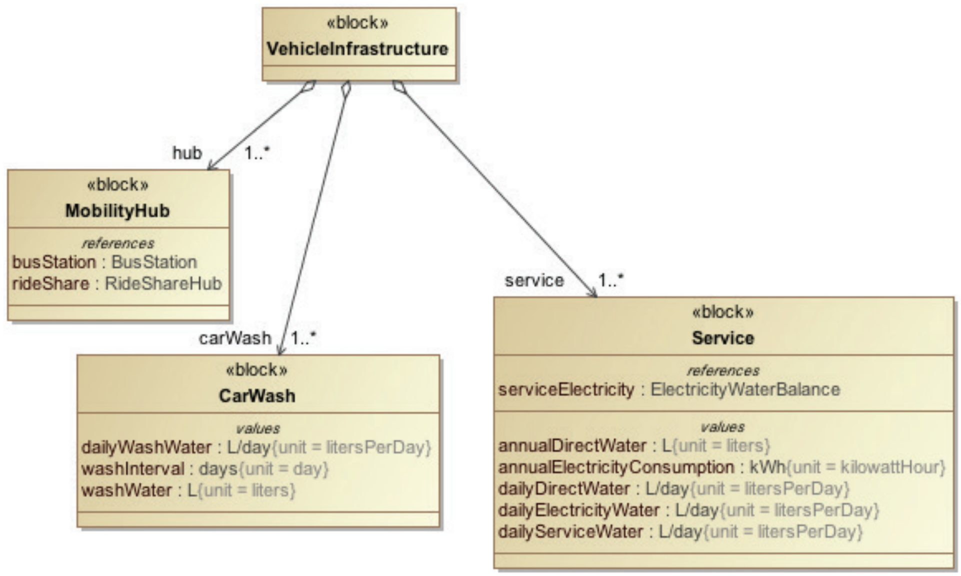


Figure 61. Vehicle Infrastructure Structural Breakdown.

One other infrastructure component defined in this sub-domain is the set of mobility hubs integrating transportation modes and services for passenger vehicles and buses; in this model structure, the **MobilityHub** block includes one or more mobility hubs pertaining to bus stations or other transit stations as well as to vehicle or ride sharing hubs – since these are the two transportation modes being assessed in this model, the mobility hub options are limited to the hubs or facilities that support these vehicle types.

5.5. Developing the Analysis Models in SysML

While the previous section defines the structural composition for the urban mobility network along with corresponding parameters and properties, these objects alone are not enough to assess overall use-phase water consumption from direct water, material, or energy flows within this network. Thus, a set of constraints need to be implemented into the model in order to integrate these parameters and perform analyses or other operations using these values to determine an aggregate water consumption value. In SysML, these are represented in the form of constraint blocks that contain mathematical constraints and connector ports for each constraint variable linked to the parameters and value properties to be assessed, as shown in **Figure 62**. These constraint blocks would ideally be linked directly to structural blocks as constraint properties so long as these properties are solely linked to the structural element being assessed.

Figure 62. Example of a Constraint Block in SysML.

However, in many cases, these constraints are reused for multiple analyses of differing structural or behavioral elements, or as Friedental et al (2008) explains: “the constraints on block properties may vary based on the current context or analysis requirements” such as in applying analyses of differing accuracy or type (Friedenthal et al, 2008). In the case of this model, a direct association between the structural block being analyses and a set of constraint blocks may work given that the current incarnation of this model focuses solely on analyzing use-phase water consumption, but said composition would fail if different requirements or performance analyses are included, such as for calculating network-wide vehicle emissions or for aggregating operating costs for multiple transportation modes.

Thus, the constraints and analysis elements in this model are decoupled from the structural elements being considered via an **analysis context** that consists of the structural block being analyzed along with the required constraint blocks. In these analysis blocks, the constraint properties are placed within the analysis block instead of in the structural object being assessed (**Figure 63**). Decoupling the constraint blocks and structural blocks and placing them into dedicated analysis contexts instead allow for a more flexible analysis model such that constraints can be used for multiple analyses and that structural blocks can be associated with multiple analyses without confusing modelers or stakeholders in terms of what is actually being assessed.

Given that a multi-modal transportation network such as the one described in this model has a large number of physical and logical elements that each contain multiple parameters, it is evident that a single analysis context in terms of water consumption for this model would not be useful as it would by confusing to follow and difficult to trace regarding the modeling and analysis requirements discussed earlier. Thus, this model's analysis portion has been broken down into multiple analysis blocks, from which a top-level water balance analysis would consist of lower-level sub-domain and component water consumption analyses. **Figure 63** shows the "structural" breakdown of the analyses being conducted in this model and how they are linked to the network-level water consumption analysis stored in **MobilityNetworkWaterBalance**. Each analysis block defined in this hierarchy contains lower-level analysis contexts or constraint blocks as part properties while structural elements such as vehicle systems or infrastructure are aggregated or referenced in these analyses. The analyses are used to allocate and calculate the daily use-phase water consumption of individual vehicle modes and road/vehicle infrastructural components – for fuel and energy infrastructures, the normalized water consumption from infrastructural flows are stored in the electricity and fuel flows to be used in vehicles and corresponding infrastructure. Higher-level analyses such as **AutoWaterBalance** aggregate individual water consumption components and apply network-based parameters such as road mileage and vehicle market shares to determine the overall use-phase water consumption for each group of multi-modal elements. As with the set of common vehicle components discussed in the vehicle type structural breakdown, all of the analysis blocks reuse certain mathematical operations and constraints such as addition of two or more values or other generic expressions; these common constraints are stored in a constraint library as a group of common constraints within the Parametrics section of the model. More analysis-specific constraints are also stored within the constraint library grouped in terms of vehicle types, infrastructure, or flows (for example, fuel-related constraints are packaged under one of the sub-folders).

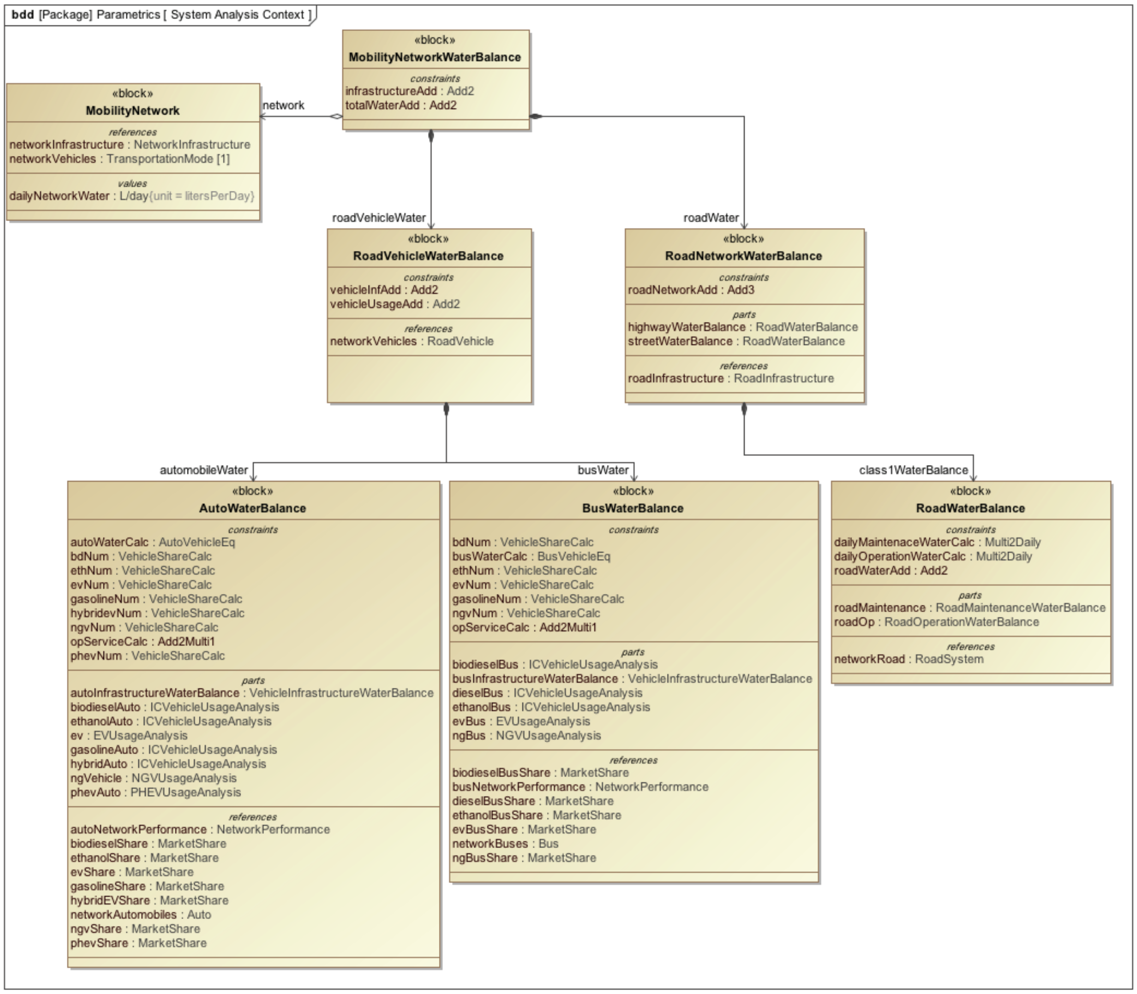


Figure 63. Mobility Network Water Balance Analysis Context and Sub-Analyses/Constraints.

5.5.1. Individual Vehicle Analysis Blocks

In an effort to compartmentalize all water consumption components for the transportation network, use-phase water consumption for the network's transportation modes is initially analyzed based on individual vehicle types or transportation modes. Thus, in addition to assessing network-wide vehicle use-phase water inputs, the model also has individual analysis definitions that pertain to each of the vehicle propulsion configurations considered in this model – IC vehicles, NG vehicles (functionally similar to IC vehicles but calculated differently due to additional fuel storage operations), electric vehicles, and plug-in hybrid vehicles. The next few subsections discuss the layout of the individual vehicle analyses, which are represented as parametric diagrams.

5.5.1.1. Internal Combustion Vehicle Usage Analysis

As discussed in the water consumption breakdown and water balance mathematical model for vehicles with internal combustion (IC) powertrains, water consumption for the use-phase of these vehicles can be traced to the water consumed in producing the fuel to be consumed, as well as to any water and auxiliary fluid inputs required for the operation of these vehicles. The production-related water consumption for each of these flows are then combined with vehicle-specific parameters such as fuel efficiency, stored volumes for auxiliary fluids and associated replacement or service intervals (either the service life or the maintenance interval depending on fluid) in order to determine fuel-derived water consumption per kilometer as well as corresponding fluid input water consumption, from where these components are added together to estimate the total use-phase water consumption for each of these vehicles per kilometer.

Figure 64 illustrates the parametric diagram used to connect these value properties to associated constraint properties that are stored within the analysis block. As explained in the idea of the analysis context, the vehicle being considered exists in this analysis as a shared property that is aggregated by the analysis block, while constraints are expressed as constraint properties associated with the analysis itself. Water consumption related to the production of associated fuels and material flows are handled separately in lower-level analyses and are treated as part properties in this analysis.

It is important to note that these analysis contexts merely provide a framework in which parameters for structural definitions can be tied together and assessed; these value properties may contain differing values depending on the fuel being considered in the analysis, which is handled by the instance specifications of vehicles using IC components. It is also important to note that in addition to gasoline, diesel, and biofuel vehicles this analysis also is attributed to grid-independent hybrid electric vehicles as HEVs can be similarly treated as IC vehicles during their use-phase as they have the same inputs as those of IC vehicles.

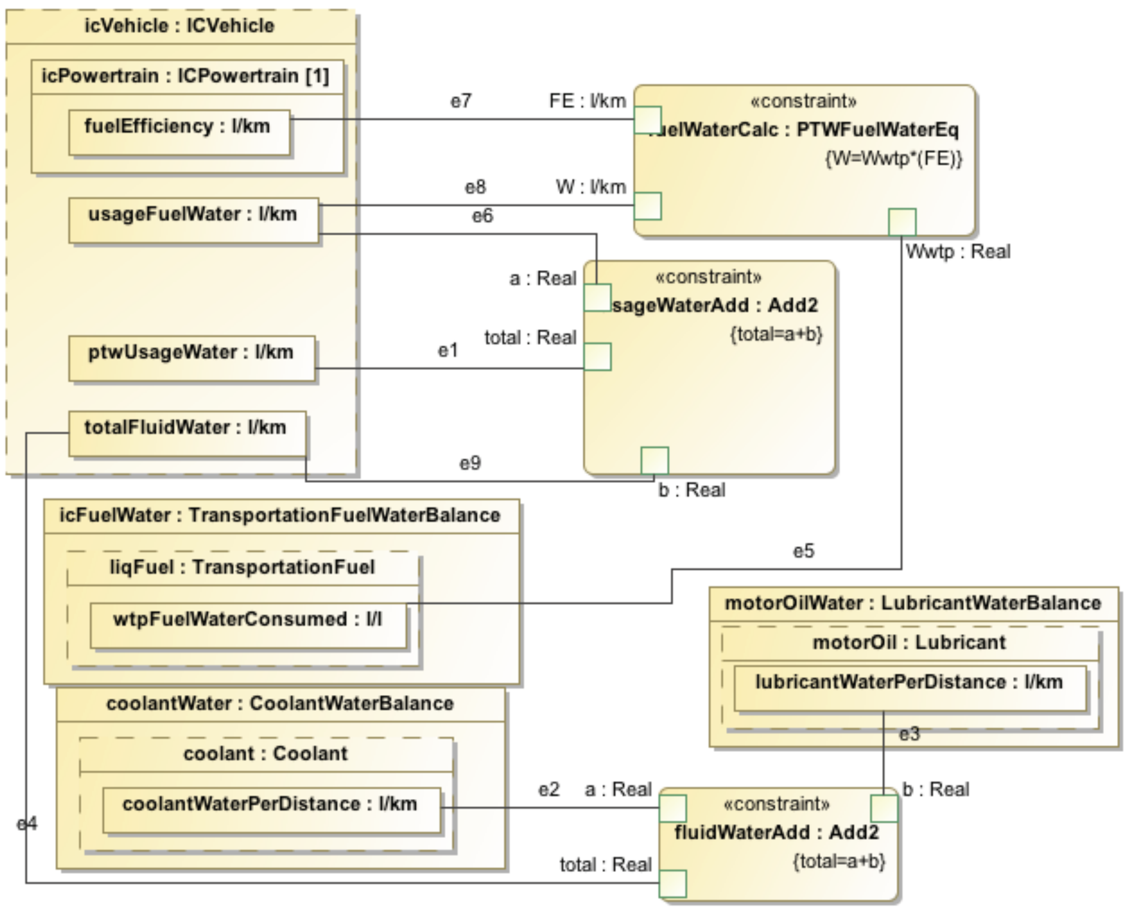


Figure 64. Internal Combustion Vehicle Use-Phase Analysis Context.

Since natural gas vehicles have similar inputs to those of IC vehicles (with the exception of the fuel being consumed), the parametric layout of the individual water consumption analysis of NG-powered vehicles is the same. However, since the water consumption for CNG production and distribution is calculated differently from that of gasoline or biofuels, the fuel-related water balance specified in this analysis context is different.

For battery electric vehicles (EVs), it was previously explained that use-phase water consumption for EVs can be traced to the amount of water consumed in producing the electricity charged to the vehicle's battery pack as well as to the amount of water consumed in producing coolant for that battery pack. As with the use-phase water consumption analysis for IC vehicles, these water consumption components (which are leveraged from individual flow analysis blocks such as water balances for fuel and coolant production) are also linked to performance parameters specific to battery-electric vehicles, such as the battery output and associated vehicle energy efficiency. Additionally, the analysis considers component efficiencies such as battery and motor efficiencies as described in the corresponding hypothetical mathematical model earlier in this chapter. As with the analysis block for IC vehicle usage, this analysis context provides a framework depicting the connections between input and output values via constraint properties and connectors, and the same analysis is used (but instanced separately) for both passenger vehicles and public transit vehicles using electric powertrains.

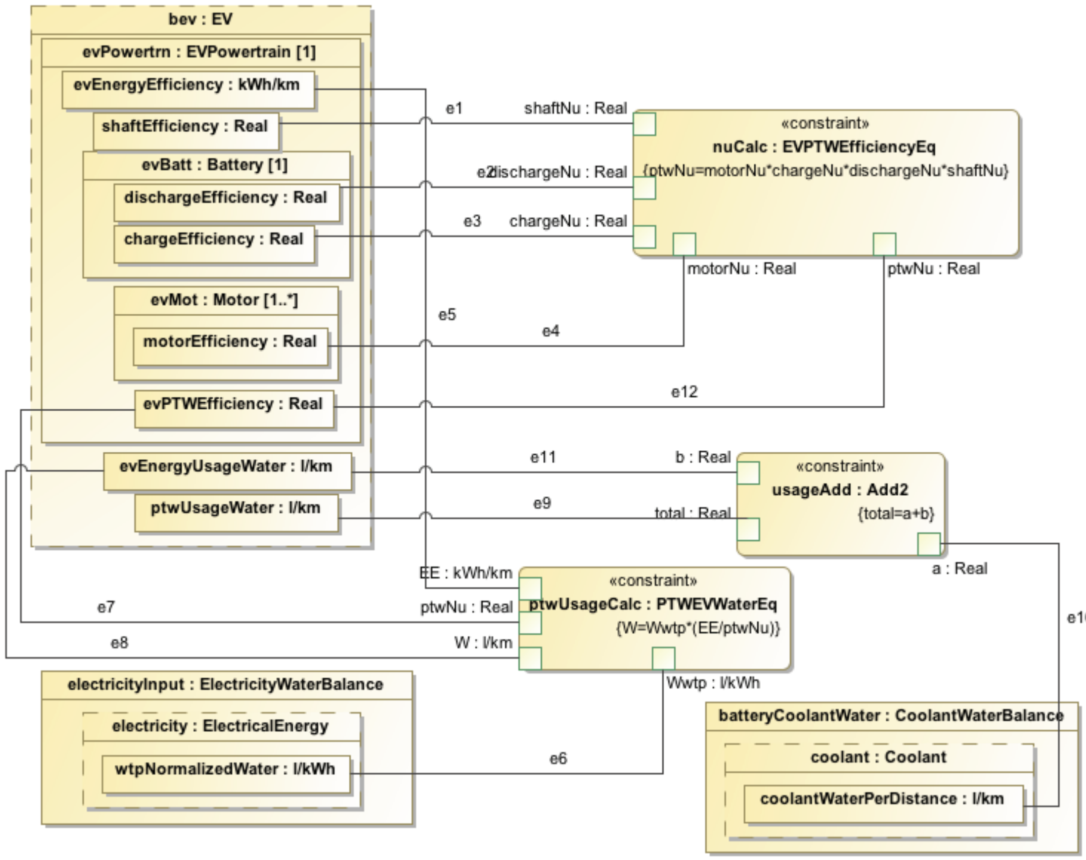


Figure 65. Electric Vehicle Use-Phase Analysis Context.

5.5.1.2. Plug-In Hybrid Vehicle Usage Analysis

Another vehicle-specific water balance to consider in this model is for the use-phase water consumption for plug-in hybrid vehicles. As noted in the structural and water consumption breakdown for PHEVs, water consumption during PHEV operation can be traced to water consumed in producing both the electricity needed to operate the electrical powertrain components and the fuel consumed in the vehicle's IC powertrain. These water consumption components are allocated similarly to those of the EV and IC vehicle analyses in addition to corresponding coolant and lubricants for each group of powertrain components and performance characteristics such as energy or fuel efficiency pertaining to vehicle operation (**Appendix A.4.1.1.**).

5.5.2. Fuel and Energy Water Balance Analyses

5.5.2.1. Fuel Water Balance Analysis

As shown in the previous sub-section pertaining to vehicle type water consumption analyses, corresponding fuel and energy inputs for these vehicles are defined separately and handled in their own analysis context blocks. While the vehicle analyses reference the produced energy sources in their analyses, these energy sources merely have aggregated or normalized virtual water intensities as their key parameter. In order to estimate these parameters, each energy flow needs to be linked to its corresponding production and distribution infrastructure within these analysis blocks.

Figure 66 details the parametric diagram used to lay out the analysis context for calculating the water balance for transportation fuels such as petroleum and biofuels. The analysis links water consumption parameters traced to the fuel's extraction source, production plant, and distribution network components such as for fuel or material transportation – these value properties are linked to the virtual water intensity in the TransportationFuel reference property via a constraint property containing the variable ports and water balance expressions discussed in the proposed math model for fuel water consumption. A separate water balance utilizing the same layout is used for thermoelectric fuels for electricity generation; however, as the value properties for these fuels in terms of water consumption have differing units this analysis is defined separately. The resulting output value within the fuel reference property is then linked to the vehicle usage analyses where this analysis block is a part property of those analysis blocks.

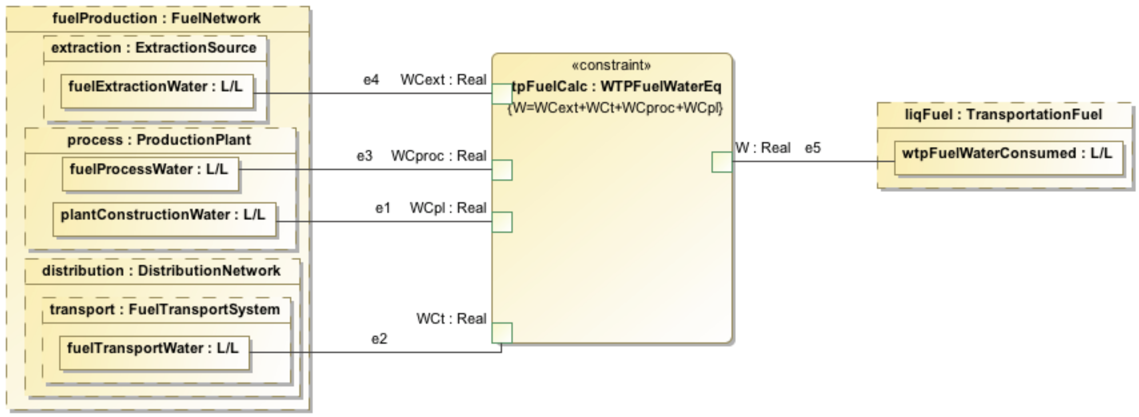


Figure 66. Transportation Fuel Water Balance Parametric Diagram.

As previously discussed, compressed or liquefied fuels such as CNG require a base fuel such as natural gas as well as additional inputs for fuel compression and storage. Thus, the above water balance for non-compressed transportation fuels is augmented to include electricity and other inputs required for fuel storage as shown in **Figure 67**. The compression ratio and compression electricity requirement values, which are value properties of the FuelStorage block, are combined with the fuel water balance for uncompressed natural gas in order to determine a water consumption value that accounts for these extra electricity and gas inputs. It is assumed in this analysis that half of the CNG in this mobility network is compressed through natural gas injection, while the other half is processed using electric compressors (King and Webber, 2008 (1)).

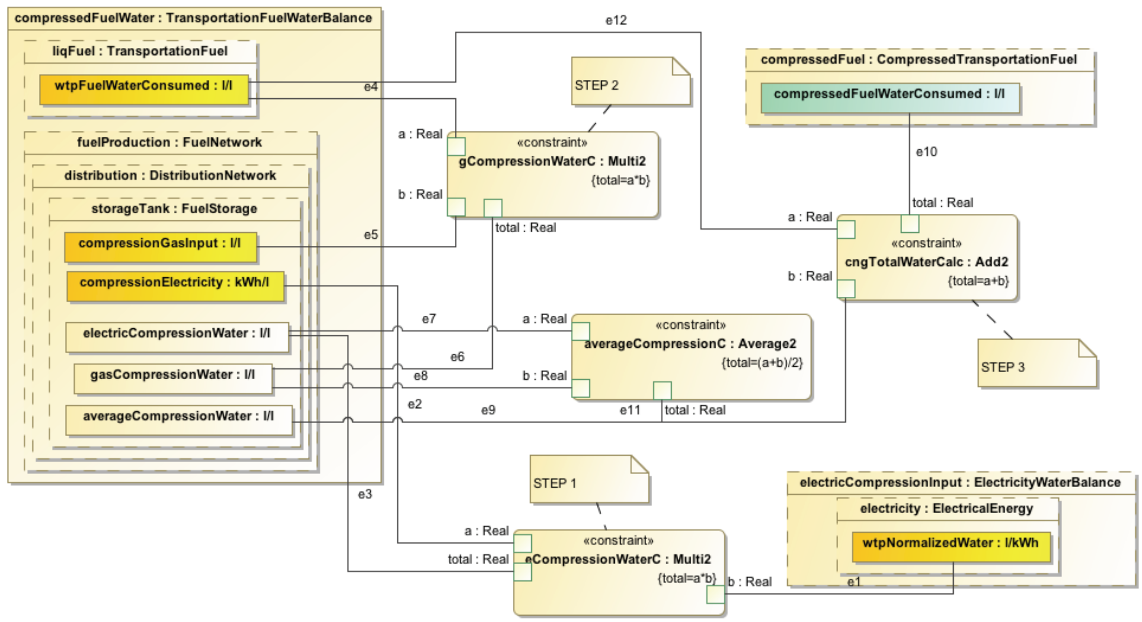


Figure 67. Compressed Transportation Fuel Water Balance Parametric Diagram.

5.5.2.2. Electricity Water Balance Analysis

As discussed in the structural breakdown of the electrical grid for this mobility network, electricity generation can be classified in terms of thermoelectric energy generation sources and renewable sources. Similarly, water consumption can be traced to the amount of water inputs required for each power plant type as well as water consumed during the operation and maintenance of renewable generation facilities. As there are numerous sources for each category, these generation types are bundled separately where individual and overall water consumption values are linked to water balance constraint properties.

Figure 68 shows the analysis context layout for calculating aggregate water consumption tied to thermoelectric electricity generation. The individual thermoelectric fuels required for electricity generation are handled in separate analyses and are then leveraged as part properties from where the aggregate water consumption value for each fuel is tied to its corresponding plant. From there, these plant-specific analyses are aggregated in a top-level thermoelectric generation water balance analysis, where all of the resulting values in each analysis are added together as shown in in **Appendix A.4.2**. For each of these generation sources, the resulting value is the total amount of water consumed for all plants within the specified fuel category (ex: coal-fired plants or natural gas-fired plants) along with a corresponding generated energy output attributed to each fuel; these values are used in the top-level aggregation for all thermoelectric plant types in order to determine a combined amount of water consumption and output energy.

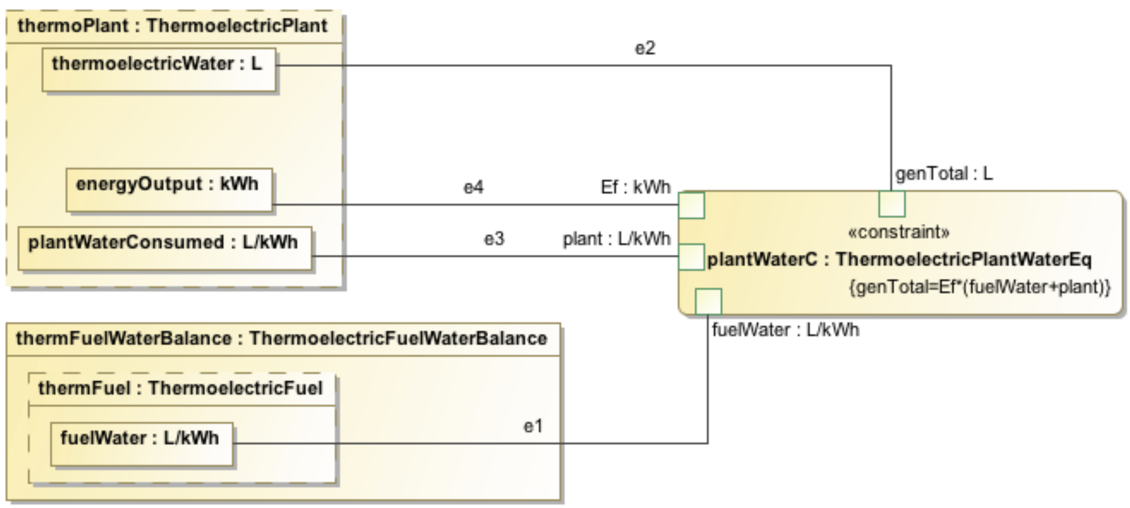


Figure 68. Water Consumption Balance for Individual Thermoelectric Generation Types.

A somewhat simplified water consumption analysis can be done with renewable energy sources, which in this model is specifically defined as solar, wind, or hydroelectric plants (biofuels are consumed in thermoelectric plants so they are combined with the thermoelectric generation analysis to maintain consistency). As explained earlier, the water consumption for these plants is traced primarily to water consumed in the operation or maintenance of these plants, mainly in terms of evaporative losses. Another value property defined in the RenewablePlant block, the water consumption amount attributed to the construction of these plants, is also used in the analysis, although some of these plants may already be constructed in certain regions. Ultimately, these water consumption components are multiplied with the energy output for each plant type to determine the total amount of water consumed for each set of renewable energy plants as shown in **Figure 69**; multiple properties of these analyses are used in an aggregate water balance for the electric grid's renewable generation distribution as well.

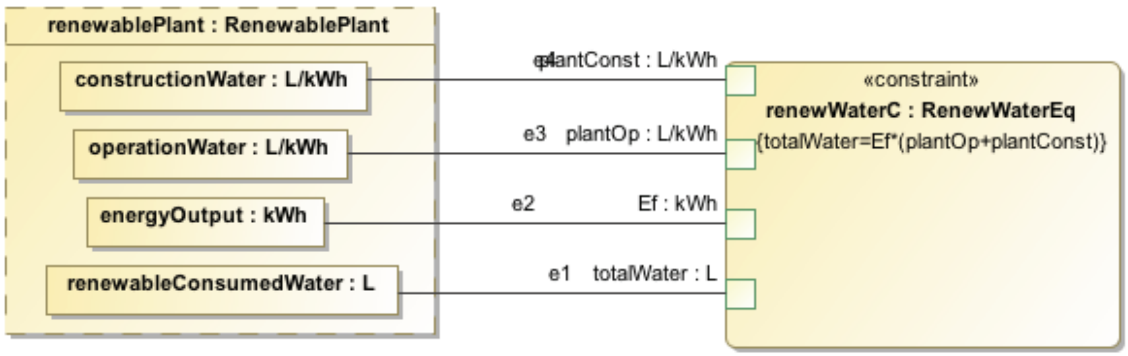


Figure 69. Water Balance for Individual Renewable Plant Types.

Ultimately, both aggregate water balances for thermoelectric and renewable generation are defined as part properties for the overall electricity network water balance as shown in **Figure 70**. The total energy output for each category, along with the corresponding total water consumption value properties, are added together; ultimately, the total water consumption value is divided by the total energy output as well as the transmission efficiency of the distribution grid to obtain a normalized water consumption value **wtpWaterConsumed** which is stored in the energy flow specified in **ElectricalEnergy** as this is the object being used by individual vehicles and infrastructure and not ElectricityNetwork, as initial versions of this model specified.

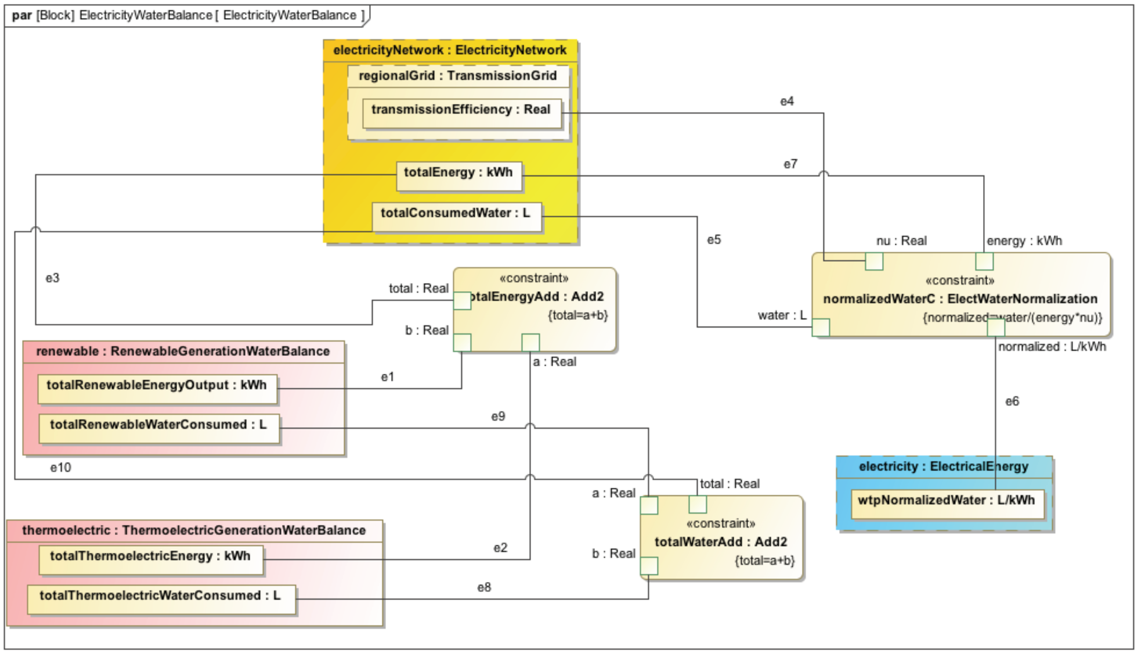


Figure 70. Electricity Generation Water Balance Analysis Context Layout.

5.5.3. Network-Level Transportation Mode Analysis Blocks

In order to determine the total daily water consumption value attributed to specific transportation modes for this mobility network, all of the vehicle types used within this system need to be aggregated along with network-specific parameters such as daily travel distances, passenger numbers, and vehicle market shares. To do this, two aggregate water balances are defined for the transportation modes considered in this system model – one for all of the passenger vehicles (automobiles), and one for the group of public transit buses within this network. Each of the vehicle type usage analyses are added to this analysis block as a set of part properties, with vehicle type variations such as biofuel vehicles for IC vehicles are represented as additional part properties of the same vehicle analysis block as shown in **Figure 71,** where the calculated use-phase water consumption is linked to a constraint property containing the total water balance for the set of transportation modes being considered.

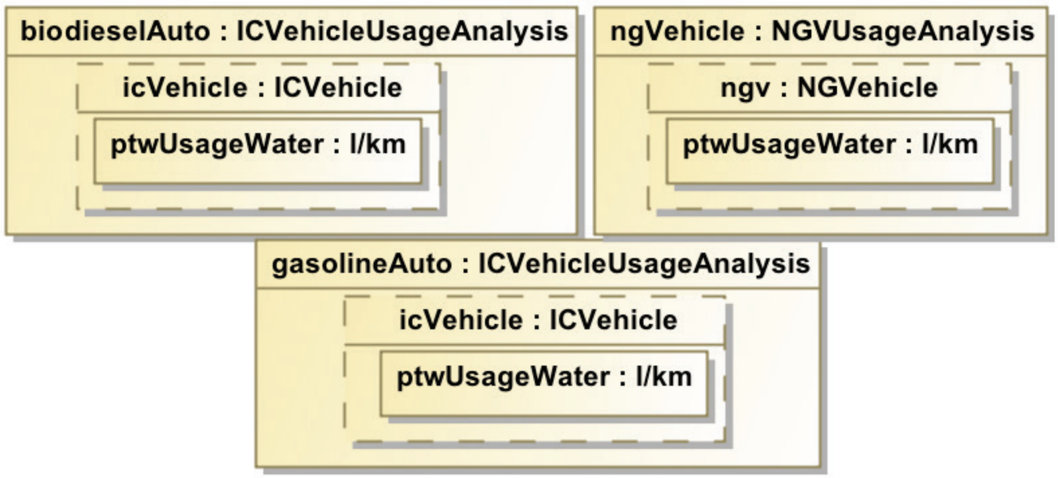


Figure 71. Assessed Vehicle Types Represented in Analysis Part Properties.

Another set of properties associated with this water balance pertains to the market share for each vehicle type represented as the **MarketShare** block, where its value properties include the market share percentage and resulting vehicle quantity (**Figure 72**). Based on a given total number of passenger vehicles and buses and market share percentages provided by the EPA's VISION scenario projections or from regional transportation agencies, the number of each vehicle type within the assessed mobility network can be determined. These market share quantities are multiplied with their corresponding vehicle type's water consumption values, and all of these products are added together using the water balance constraint **AutoBalanceEq** as shown in the beginning of **Section 5.5**.

Figure 72. Example of MarketShare Block Usage in Water Balance Analysis.

Network parameters pertaining to the daily driving distance for each group of transportation modes within this network are stored as value properties in the **NetworkPerformance** block, which is also aggregated as a shared property in this analysis block and multiplied with the previous sum to determine the daily water consumption attributed to vehicle usage – the corresponding output value **dailyPassVehicleUsageWater**, along with the input value pertaining to the total number of vehicles on the road in this mobility network, is stored in the **Auto** sub-domain block as shown in **Figure 73**. Another output value pertaining to the total daily water consumption attributed to vehicle infrastructure is also stored in the Auto block, with the input values for this portion of the analysis being the daily water consumption (per vehicle) for vehicle servicing and washing. This analysis structure is also used for calculating the daily use-phase water consumption for buses; however, as the scope of bus propulsion configurations is limited to biofuel-powered, diesel and natural gas-powered, and battery-electric buses, the top-level water balance for this transportation mode has fewer market share and water consumption input variables.

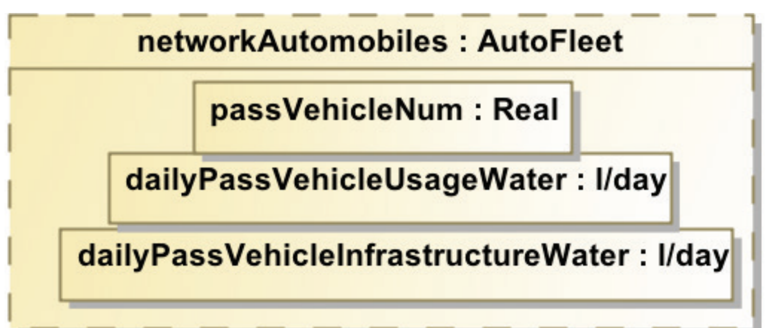


Figure 73. Auto Sub-domain Block Reference.

Both transportation mode analyses are then integrated into a upper-level water balance estimating the total daily water consumption from transportation mode usage as well as the total daily water consumption from the corresponding infrastructure need to support such usage, as shown in the **RoadVehicleWaterBalance** parametric diagram in **Figure 74**.

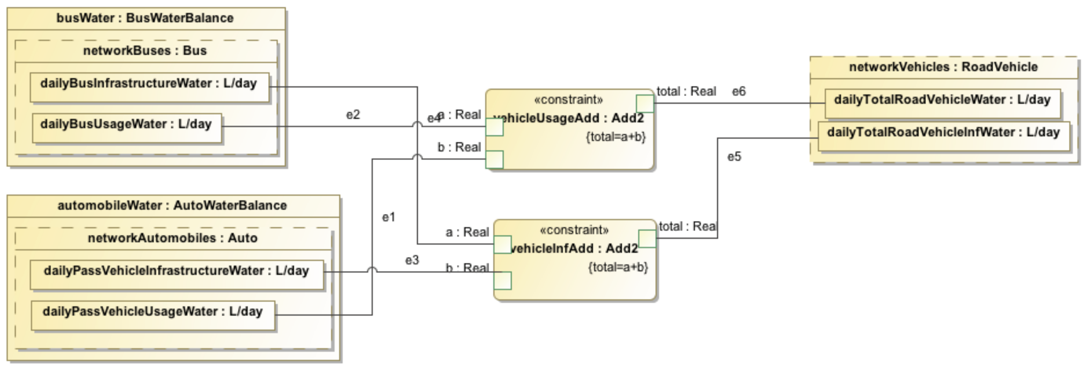


Figure 74. Road Vehicle Water Balance Analysis Context.

5.5.4. Road and Vehicle Infrastructure Analysis Blocks

While the energy and fuel network infrastructures are integrated with their respectively produced energy flows in the fuel and electricity generation water balance analyses, the vehicle and road infrastructures are ultimately handled similarly to the individual vehicle type and aggregated transportation mode analyses. The next few analysis contexts to be discussed comprise the water requirements balances for road infrastructure components on an individual road configuration level as well as on a network level.

In conforming the with intention to assess the use-phase water consumption of transportation-related components and sub-domains, the road-specific, usage-based water balance analyses will be calculated for individual road types (streets, connectors, and highways) and added together to determine the overall use-phase water consumption from a multi-modal transportation network's roads. However, unlike the individual vehicle type analyses that focus mainly on usage inputs, the use-phase water consumption for each road will be separated based on water consumption incurred when operating these roads and water consumption incurred when maintaining (ex: resurfacing and repainting) these roads. This separation was based on the life cycle data presented for Swiss road networks as presented in Spielmann et al (2007) where life cycle material and energy flows were separated between road operation and road maintenance.

Figure 75 shows the overall analysis context for the road infrastructure sub-domain being considered in this system model, where the **RoadNetworkWaterBalance** contains separate road configuration analysis blocks (**RoadWaterBalance**), where each road type analysis contains separate use-phase water consumption analyses for both road operation-related expenditures and road maintenance inputs. As with the vehicle analysis breakdown discussed in **Section 5.5.1**, the RoadSystem block (which represents the group of infrastructure components comprising a road within an urban mobility network) is referenced multiple times as it contains multiple ancillary values that are required by each of these analyses. The operation and maintenance water consumption analyses are discussed further in **Appendix A.4.3.1.**

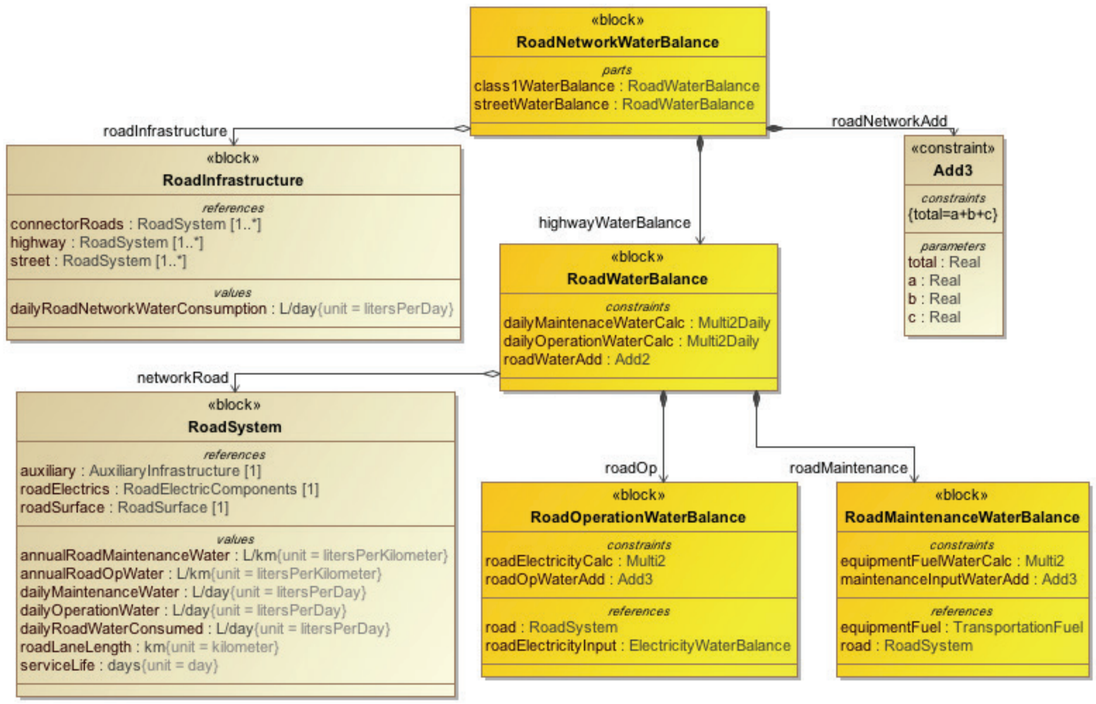


Figure 75. Road Infrastructure Sub-domain Analysis Context.

Both analysis blocks pertaining to road operation and maintenance-related water consumption are integrated into an upper-level water balance intended to estimate the total daily amount of water consumed for these two activities. **Figure 76** shows the integration of these two analyses along with constraint properties, where the resulting values for each analysis block are combined by these constraints to an output value.

That said, as the input value properties for each of the operational and maintenance input water balances are presented in an annual basis, additional mathematical operations are needed in order to convert these values to daily water consumption rates. For this model, it is assumed that the annual water consumption for these inputs are evenly distributed across each year; that said, seasonal inputs such as sale for de-icing would need to be left out of the analysis during the time periods when they are not needed for normal usage of these roads. This conversion to daily water requirements is handled by two constraint properties as shown below.

Another key input variable within this analysis block is the lane distance amount **roadLaneLength** that represents the number of kilometers of lanes for a specific road type. In order to determine the total daily use-phase water consumption for each group of roads, this is combined with the per-distance water consumption traced to material and energy inputs associated with either set of activities. Furthermore, in order to track the distribution of water requirements for road usage, there are also two ancillary values for the total daily water consumption for either maintenance-related activities or operational activities. It is assumed that both of these output values (in addition to the total value specified by **dailyRoadWaterConsumed**) assume that the amount of material and energy inputs and associated water consumption are uniform across each set of roads within this network.

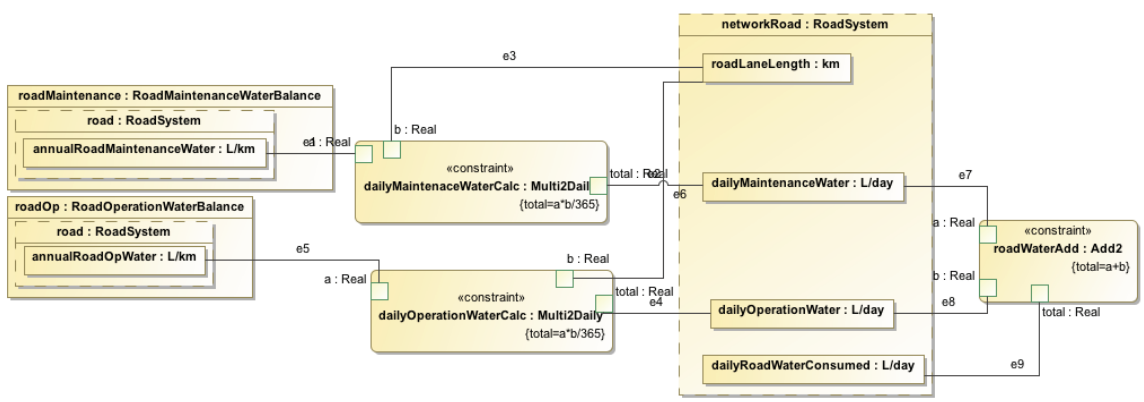


Figure 76. Water Balance Aggregation for Each Road Classification Group.

The above analysis block is then included as multiple part properties of a network-level road infrastructure water balance analysis shown below in **Figure 77**, where part properties corresponding to each group of roads (connector roads, streets, and highways). This sub-domain water balance **RoadNetworkWaterBalance** itself will be included as part of the system-level water balance that integrates top-level daily water consumption for both the transportation modes and mobility infrastructure within this network, which will be discussed shortly.

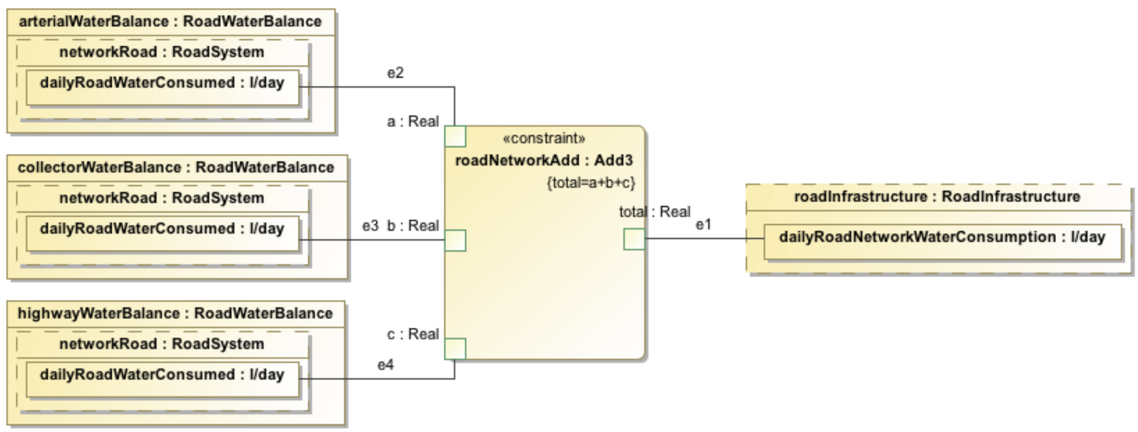


Figure 77. Water Balance Aggregation for All Roads.

5.5.4.1 Vehicle Infrastructure Water Consumption Analysis

The other infrastructural water analysis in this model pertains to the set of vehicle servicing and washing facilities along with a network of dedicated mobility hubs within this transportation system. While there is not enough life cycle data for this model to assess water consumption impacts for mobility hubs without making rough assumptions, there is life cycle data on the amount of water inputs and energy inputs required for vehicle servicing facilities as well as for how much water is used in car washes for each vehicle type. These input values are combined together within an analysis block that links these values to constraints in order to determine the daily water consumption for each set of facilities per vehicle.

Figure 78 summarizes the analysis context for determining daily water consumption from vehicle infrastructure usage. As with the water balance analysis for road classification groups, input data for vehicle service facilities are allocated on an annual basis and would need to be converted to daily inputs; while there are two data sets for automobiles and buses, the passenger vehicle service inputs are based on a compact passenger vehicle with an IC powertrain; for this model, it is assumed that the direct water and electricity inputs for these service facilities are uniform across all vehicle types (material inputs such as coolant and lubricants are handled separately in analysis blocks for each vehicle's usage). Since it is assumed that the water and electricity inputs are the same for all vehicle types within either set of road transportation modes, this analysis block and associated output values are leveraged in the top-level water consumption balance for either transportation mode instead of in individual vehicle analyses.

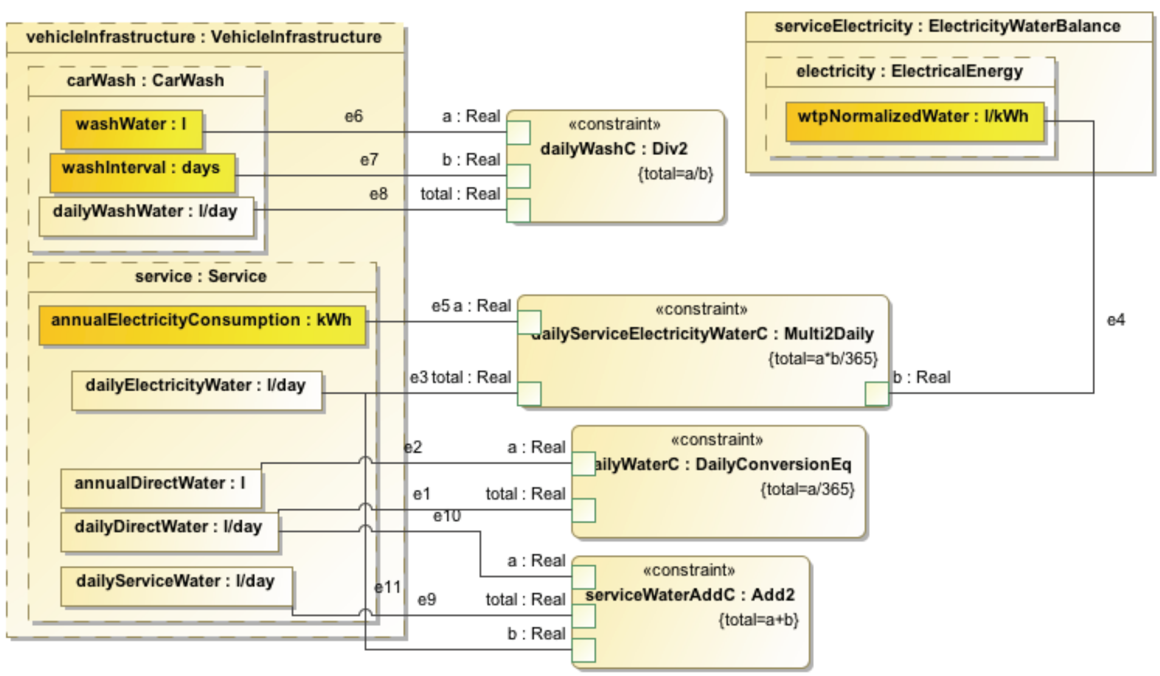


Figure 78. Vehicle Infrastructure Water Consumption Analysis Context.

5.5.5. Bringing It All Together: The System-Level Water Consumption Analysis

All of the preceding analysis blocks at the component and sub-domain levels are ultimately linked to the system-level analysis block as shown earlier in **Section 5.5**. The transportation mode usage water consumption analyses are combined with the infrastructure usage water analyses and corresponding output values to determine the total daily water consumption within a multi-modal transportation network based on the vehicles and network components included in the analysis. **Figure 79** illustrates the layout of the top-level water balance analysis block, where the vehicle infrastructure-related water consumption value is added to the road infrastructure water consumption value property in order to determine the total daily water consumption attributed to the use-phases of these infrastructure groups. Finally, this aggregate value is combined with the total daily water consumption attributed to transportation mode usage in order to estimate the overall water consumption value for the entire transportation system.

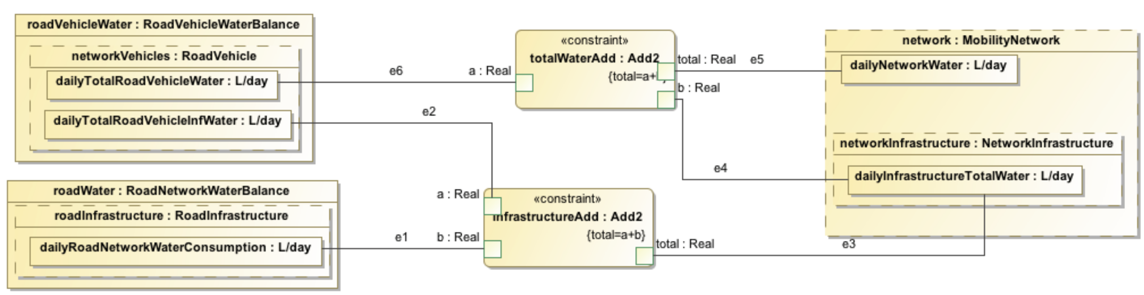


Figure 79. Water Consumption Analysis for the Entire Mobility Network.

CHAPTER 6

CASE STUDIES: OVERVIEW AND INPUTS

6.1. Overview

Now that the system model in SysML has been explicitly defined using MBSE principles in order to assess top-down daily water consumption from individual components and sub-domains within a urban mobility network, it is time to apply the structural and analytical components in this model to a series or real-world and hypothetical scenarios in order to determine the extent of water impacts on current and projected transportation network conditions. This step pertains to the specification of design alternatives – in this case, specifying multiple network configurations and conditions – and evaluation of these alternatives for a given system or design that is being embodied or developed. To run these analyses, the ParaMagic plugin will be used in conjunction with SysML to convert the analysis model into a series of causal mathematical statements that are executable within an external analysis tool such as Mathematica.

The object-oriented nature of the model and the implementation of reusable elements in this SysML allows for the specification of multiple instances – and ultimately the application of multiple scenarios for a given case study – of individual components and domains within this multi-modal transportation system. The case studies to be executed within this model and associated analysis tools will focus primarily on the Atlanta metropolitan area and its associated automobiles, buses, and mobility and energy infrastructures. Fuel and energy characteristics along with vehicle performance parameters are based on data provided by other life cycle models or statistical databases;

network-based parameters such as road mileage and daily travel distance are based off of data provided by regional transportation agencies and mobility-focused reports or databases. In addition to baseline conditions in Atlanta for 2010 energy and vehicle distribution profiles, the model will also incorporate projected energy and fuel distributions for 2030 as well as implementing alternate electricity and fuel scenarios for hypothetical network conditions. **Chapter 7** will also highlight the results of each scenario in order to determine the potential impacts of implementing alternative fuel and energy pathways into a transportation network with respect to local freshwater requirements and availability; furthermore, the overall trends in these scenarios and the validity of the model and its calculations will be considered.

6.2. Implementation Using ParaMagic and Mathematica

While SysML is a modeling language developed primarily to support the implementation of systems engineering activities such as specify and tracing requirements and defining the physical structure of a system or entity, it cannot run numerical analyses even though it has the capability of specifying analysis blocks and defining relationships between object parameters and constraints. In other words, SysML is a primarily descriptive language that allows for the same activities and procedures within a system model that engineers would normally document on paper, but it is not necessarily an executable language for conducting quantitative analyses or evaluations. As defined in SysML, a system model such as the model framework described in the previous chapter is intended to capture requirements, structure, behavior, and parametric elements relevant to an actual system and its surrounding environment (Friedenthal et al, 2008).

That said, SysML and UML have been built on the foundation of object-oriented modeling and the inclusion of multi-scale objects and their interconnections such that models developed within these languages can serve as a foundation for augmenting such framework to incorporate executable model components ranging from verification and simulation models to network or discrete-even analysis models. In addition to object-oriented definitions inherent in UML and SysML, the model information specified within the Systems Modeling Language is stored in a "neutral" file format that can be leveraged to exchange model information and data with external development and analysis tools – in this case, the backbone of SysML model files is that of the Extensible Markup Language (XML), which is a set of open source document encoding methods intended to be used for a wide range of applications (Bray et al, 2008). From these two foundations, SysML models can potentially be repackaged and integrated with external tools and frameworks within their surrounding systems development environment (Friedenthal et al, 2008; **Figure 80**).

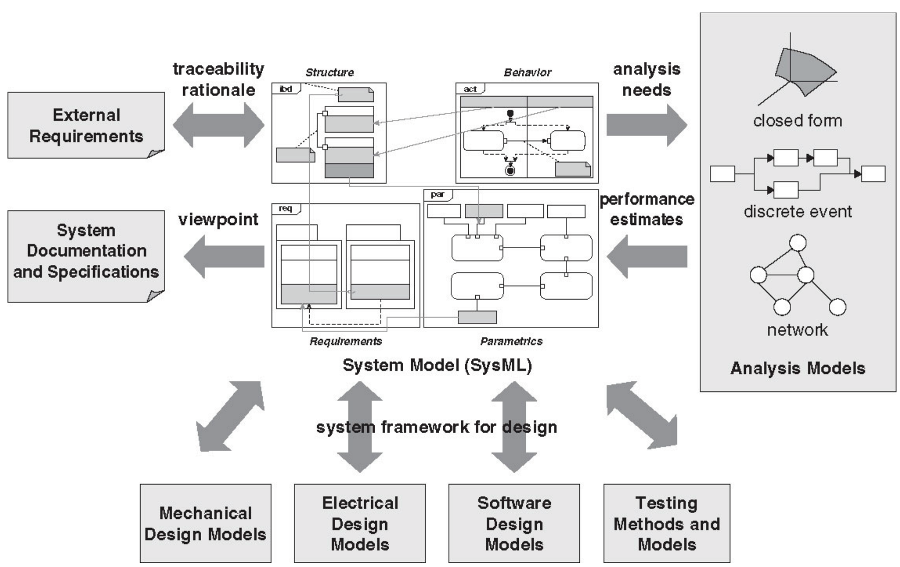


Figure 80. Integration of SysML Model With System Development Environment (Friedenthal et al, 2008).

6.2.1. Instance Specifications Overview

One method to integrate SysML model information with external analysis models is to convert such information into a set of executable statements that can be read by other software packages and languages. In the case of this model, case studies can be defined as a set of **instance specifications** that store unique values or properties based on the blocks defined in the system model's structure. In other words, the blocks defined within the model's structure or analysis context ultimately describe, "a set of similar instances, or objects, each of which exhibits the features defined by it" (Friedenthal et al, 2008). For example, the ICVehicle block in the model's structure, along with its comprised mechanical or electrical components, serves as a template for multiple instances specifying biodiesel automobiles, CNG-powered buses, and all other IC-based vehicle types considered in this network (**Figure 81**). Similarly, the MobilityNetwork block provides a framework for specifying a particular region, such as for the transportation network in the Atlanta metro area.

Figure 81. Instance Specifications of ICVehicle.

Similarly, analysis blocks defined in the model can serve as frameworks for instances that integrate the instances of each analysis's referenced structural blocks, such as the analysis instance specification shown in **Figure 82** for an individual vehicle type. Each instance contains a set of input and output **slots** that correspond to the properties within the block the instance is associated with – part and reference property slots within an instance block can be associated with a particular instance that is typed by the same structural or analysis block as that of the parent block's properties; on the other hand, value property slots pertain to numerical or string entries that are unique to each instance of the associated block. Given that many analysis blocks within this model reference a single set of blocks containing universal properties or variables as part of their analysis context, the corresponding instances for these analysis blocks can all link to a single group of instances specifying common or global elements for a given region.

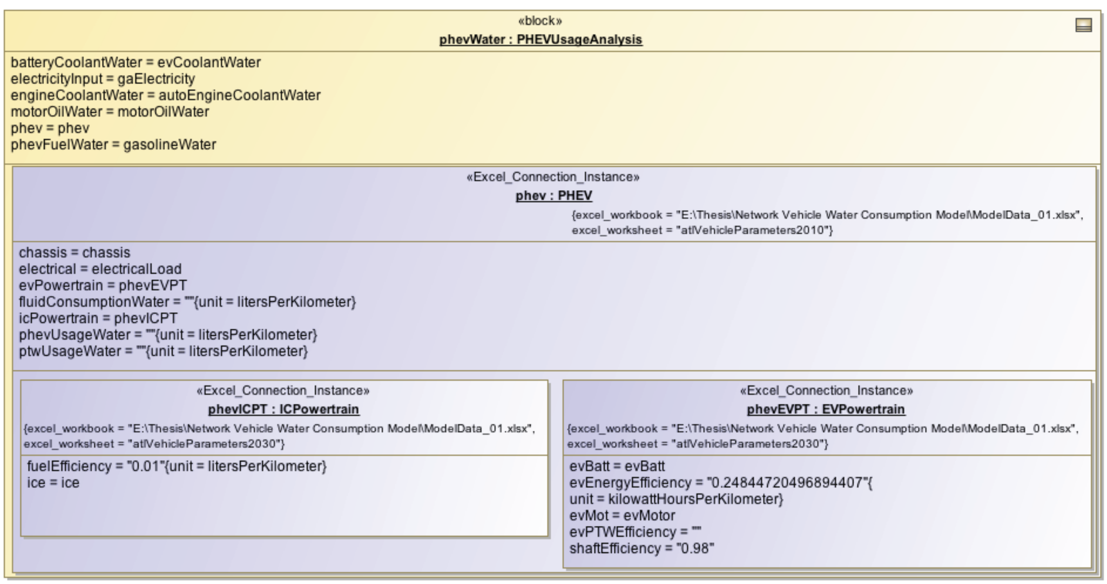


Figure 82. Analysis Block Instance for PHEVUsageAnalysis.

Although the fact that multiple instance specifications that reference the same child instance reduces model clutter and facilitates the reusability of elements for different viewpoints or contexts in the system model, the collective set of instance specifications for a given transportation network are still very complex and expansive**.**

6.2.2. Converting Model Information Using ParaMagic

The properties and relationships presented in these instance blocks for a particular case study or scenario serve the basis of the information to be exchanged between SysML and the associated model to an external analysis tool. One tool to facilitate this information exchange is the ParaMagic plugin developed by InterCAX LLC and provided as an add-in to the MagicDraw UML application, of which SysML also exists as a plugin. Like SysML, the ParaMagic plugin includes a language profile that parses the information presented within these instance specifications and transfers such information to an external tool such as Mathematica or MATLAB. While other analysis integration tools are available or are being developed, such as MATLAB-based or ModelCenter-based conversion tools, ParaMagic is closely integrated with MagicDraw and SysML and has been refined over the past several years such that current iterations of this tool are stable enough to perform repeatable analyses.

The basic premise of ParaMagic is to translate the model's parametric elements into a network of solvable equations within this system model, where each variable within these equations would need to be classified either as known (given) or unknown (target) via causality assignments. Additionally, intermediate values such as output (right-hand-side) variables that are used as inputs for other equations can be assigned as ancillary variables. These inputs and outputs – either in the form of part/reference properties or variables – that are represented in the instance specifications' slots are indexed by ParaMagic and displayed and display them within a browser as shown in **Figure 83**. The assigned values and properties shown in the ParaMagic browser are interpreted as a series of symbolic equations within external analysis tools – in this case, Wolfram Research's Mathematica software. The resulting calculated values from Mathematica are then passed back to ParaMagic and ultimately the SysML model for interpretation or for further evaluation.

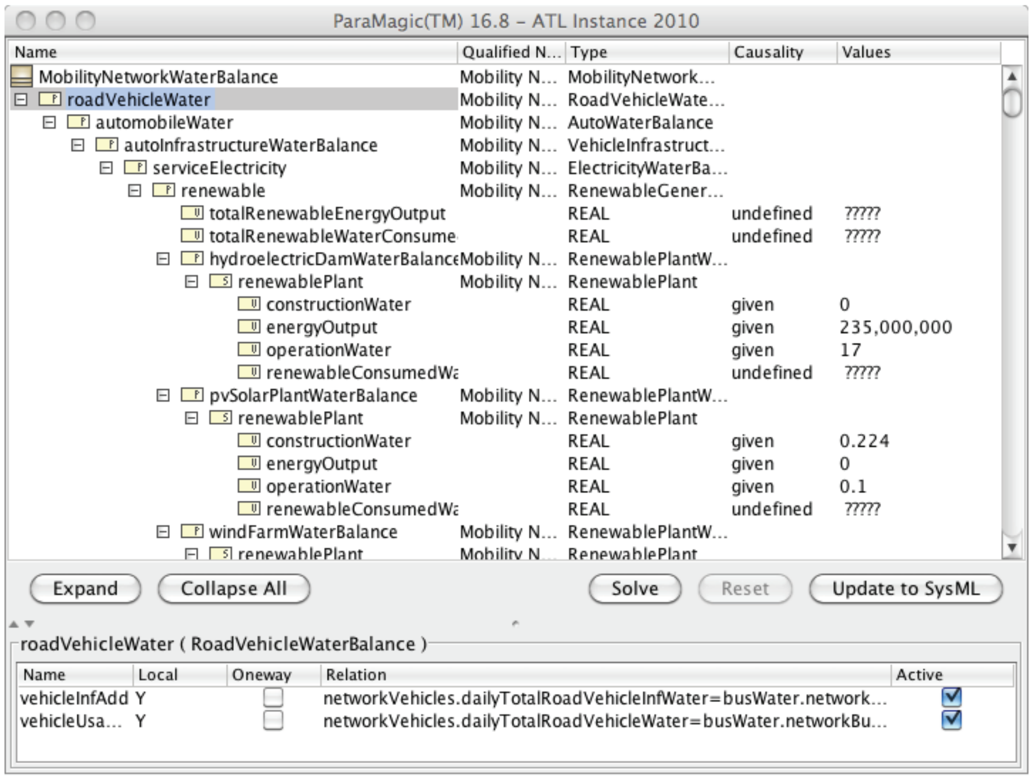


Figure 83. ParaMagic Browser Window Showing Value Properties and Parametric Elements.

6.2.3. Applying Scenario Inputs Using Excel

Another capability of ParaMagic in addition to linking model information in SysML to an external analysis tool is the ability to link inputs and outputs with spreadsheets created with Microsoft Excel (**Figure 84**). Specific cells can be assigned to corresponding value property slots for each instance such that ParaMagic can either populate these slots with the values stored in these cells or write to corresponding cells as required by the user. While it is possible to input values to these slots manually, the ability to read input values and transfer output values from and to Excel allows for the user to link existing values from a spreadsheet or data matrix for alternative scenarios without defining these values from scratch for each instance and case.

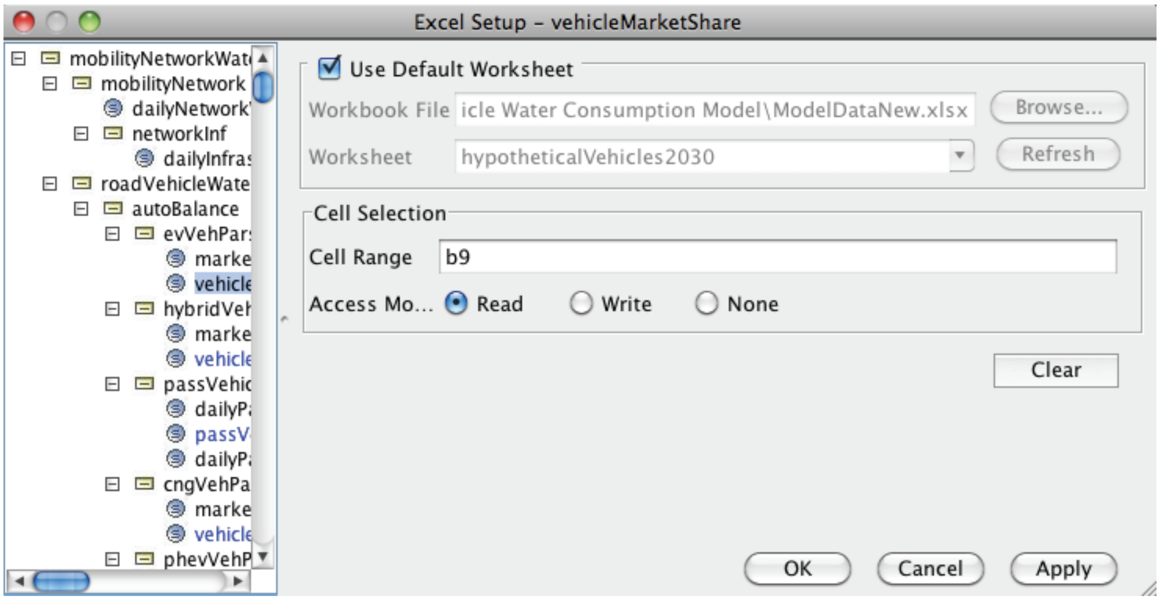


Figure 84. ParaMagic-Excel Connection Linking Slots to Spreadsheet Cells.

6.3. Network Case Study Overview

The baseline and alternative scenarios to be assessed using this system model focuses on the transportation-related characteristics of the Atlanta metropolitan area. The Atlanta region is an interesting scenario to assess given that it is one of the fastest-growing metropolitan areas in the United States and has an extensive air, rail, and road transportation network. Furthermore, as the Atlanta metro area comprises of 15 counties with numerous suburbs, the urban sprawl in this metropolitan area has resulted in the vast majority of commuters using automobiles as their primary form of transportation in this network. This heavy reliance on road transportation has placed Atlanta near the top 10 most congested metropolitan areas in the United States with an average daily commuting distance of 21.6 miles and an annual traffic delay average of 57 hours (Inrix, 2010).

Figure 85. The Atlanta Metropolitan Area (Shaded in Grey) (Source: U.S. Census Bureau).

Perhaps the most notable rationale for choosing Atlanta as the mobility network baseline for this model is that Atlanta has experienced water stresses within the past few decades, with drought conditions during the past decade as well as an increase in water demands – primarily for agricultural use but also for municipal and industrial sectors – outpacing available water resources. The Atlanta metropolitan area is situated within the upper half of Appalachia-Chattahoochee-Flint basin, which serves as its main source of water deliveries primarily from freshwater reservoirs such as Lake Lanier (Richter et al, 2000; **Figure 86**); as there are no natural lakes within the metropolitan area's surrounding environment, much of Atlanta's water supply is dependent on man-made reservoirs and surrounding rivers (Atlanta Regional Commission, 2010; **Figure 87**). As such, allocation of water resources for Atlanta has been a contentious issue for many decades as the ACF basin's water flows are also traced to neighboring states Alabama and Florida, with legal action sought starting from the 1990s regarding unchecked increases in water withdrawals from the Chattahoochee River and Lake Lanier for Atlanta. Today, water withdrawal increases from Lake Lanier for Atlanta are now strictly regulated in order to ensure that Florida, Alabama, and southern Georgia maintain consistent water supplies for irrigation and other industries (Atlanta Regional Commission, 2010).

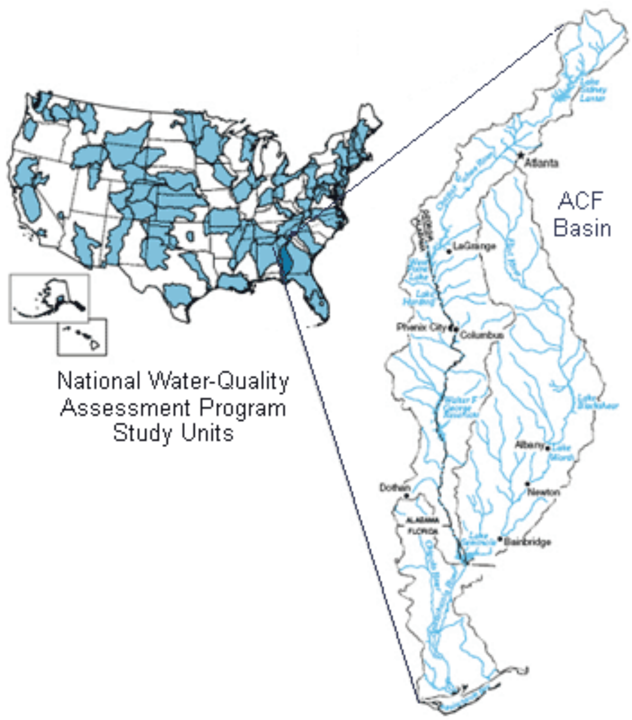


Figure 86. Atlanta and the Apalachicola-Chattahoochee-Flint Water Basin (United States Geological Survey, 2010).

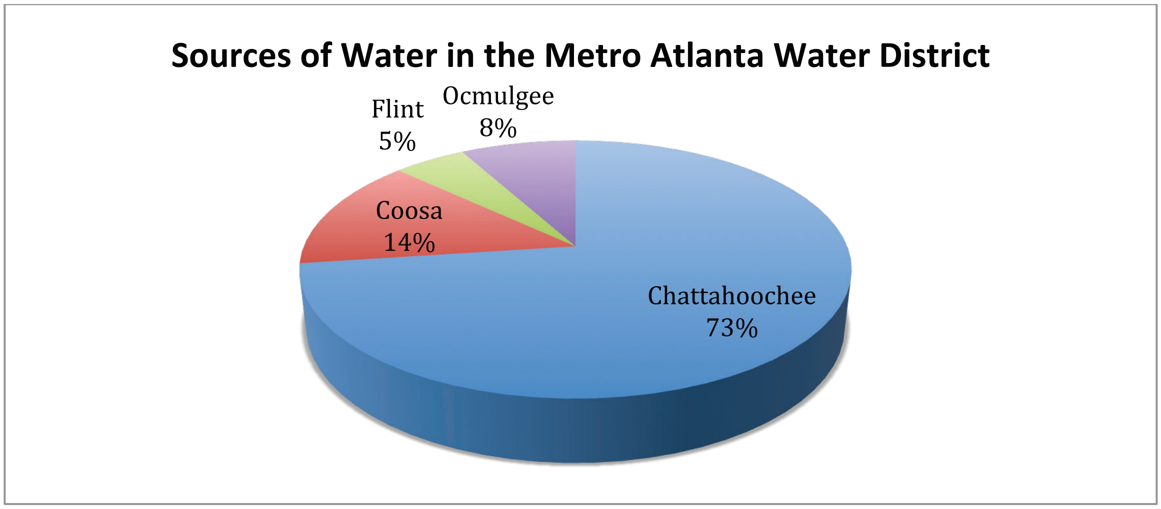


Figure 87. Distribution of Freshwater Sources for the Atlanta Metropolitan Area (Adapted from Atlanta Regional Commission, 2010).

Based on regional transportation and water supply characteristics, Atlanta is a good place to start in terms of determining the impact of certain transportation modes and infrastructure usage on local water deliveries and availability; furthermore, with the potential expansion of biofuels and alternative fuels for fast-growing regions such as Atlanta in order to improve air quality, it is important to determine how widespread production and usage of these fuels would add to existing transportation-related water demands.

6.4. Case Studies Overview

From this transportation network and with the system model previously described, several scenarios represented by input parameters will be examined to assess the impacts of variations of transportation and energy profiles for a given urban mobility network in terms of water requirements and availability.

The first, and baseline, scenario to be considered using this model reflects current transportation and energy conditions in Atlanta as of 2010 regarding the total amount of road mileage, number of vehicles and distributions of fuels or powertrain configurations, average daily driving distances, and regional electricity profiles. These parameters are leveraged from statistics provided by regional transportation agencies or from national databases on energy usage and distributions; these inputs are combined with known water consumption information for energy production and transportation-related usage inputs to calculate an overall daily water consumption amount for the transportation network against known daily water deliveries for Atlanta in 2010. Vehicle parameters such as fuel efficiency are based on existing transportation and energy systems assessments, while material inputs for road and vehicle infrastructural operation are obtained from the Ecoinvent life cycle database. As fuel and energy-related water consumption data is primarily presented as ranges with low, high, and/or average values, low-end water consumption scenarios will also be considered within this case study in order to assess the “best-case” outlook for transportation-related water consumption. In addition to determining aggregate sub-domain and network-level water consumption, water consumption ratios for each vehicle type and fuel will also be examined as these values serve as ancillaries to calculating top-level parameters.

Based on this benchmark case, several potential and hypothetical future scenarios are also assessed, where key input parameters are altered one-by-one or collectively in order to examine potential impacts from utilizing more renewable and alternative fuels or energy sources. The first projected scenario to be assessed focuses on a projected energy profile for Georgia in 2030, in which the variations in energy and fuel profiles are based on projected distributions presented in the Energy Information Administration’s Annual Energy Outlook 2010 report and vehicle efficiency improvements are based on projections made within the EPA's VISION model for 2030 conditions. Additionally, vehicle market shares will be based on the VISION model's projections while increases in transportation mode quantities will reflect projected population and mobility growth rates.

In addition to assessing energy pathways for Georgia, two more case studies will implement Washington State's electricity generation profile and network performance characteristics (in this case, a DVKT value specific to the Seattle metropolitan area) to the existing vehicle fleet and mobility network in Atlanta in order to assess the effect of significantly altering the electricity generation distribution and daily travel characteristics on individual and aggregate water consumption from vehicle and infrastructural usage.

Next, a hypothetical future case study will be considered where the current and projected energy profile for Georgia is replaced with an alternate energy distribution that has a heavy reliance on renewable generation methods and biofuels as well as on biofuel-powered and hybrid vehicles (HEVs and PHEVs). Additionally, differing fuel production technologies such as for switchgrass-based ethanol and algae-derived biodiesel will be considered.

The final scenario to be assessed expands the scope of water consumption and includes water consumption values from fuel extraction and recovery in order to assess the total impact of fuel-related and energy-related water consumption on vehicles within this network. Although such a definition technically violates the overall demand that water consumption values be limited to local water impacts, this scenario is intended to provide a comprehensive outlook of how water requirements for extracting the fuels necessary for a transportation or mobility network can affect individual and aggregate water consumption for transportation modes and infrastructure.

The overall characteristics for these scenarios are summarized below in **Table 24**. In each of these scenarios, vehicle parameters such as tank-to-wheel efficiencies and respective market share percentages will be altered depending on the year being considered; additionally, vehicle configurations for the automobile and bus fleet will be selected based on current and projected market shares, while in the hypothetical scenarios vehicle types and respective market shares are selected based on potential impacts of alternative vehicle modes on water consumption for the Atlanta metro network in the near future. While the automobile fleet's average DVKT (daily vehicle travel distance in km) can be altered based on the metro network being considered (Atlanta versus Seattle, in this case) due to the availability of region-specific parameters, DVKT and market share values for the bus fleet in this study are specific only for Atlanta's public transit system and market share percentages for automobiles are based on national averages. Electricity profiles for each state being considered comprise energy outputs and plant configurations for their respective electricity generation sources. The next few sections will detail overall characteristics for each scenario in this cast study in addition to outlining the global and scenario-specific input parameters that will be used to calculate individual vehicle mode and network-wide water consumption for the transportation system.

Table 24. Overview of Scenario Inputs.

Case	Title	Electricity Profile	Year	Autos Considered	Buses Considered	Daily Auto Travel Value, km (DVKT)
1	Baseline Case	Georgia	2010	Gasoline and Hybrid Electric, E85 Ethanol Flexfuel, EV	Diesel, CNG	44.9
2	Atlanta with Washington Electricity and Travel Stats, 2010	Washington	2010	Same as 1		35.2
3	Atlanta With Georgia Electricity Projections, 2030	Georgia	2030	Gasoline, HEV, PHEV, E85 Ethanol, Biodiesel, EV	Diesel Hybrid, CNG	44.9
4	Atlanta with Washington Electricity and Travel Stats, 2030	Washington	2030	Gasoline, HEV, PHEV, E85 Ethanol, Biodiesel, EV	Diesel Hybrid, CNG	35.2
5	Atlanta with Hypothetical Electricity Generation Mix (More renewable and emerging technologies, alternative fuel portfolio)	National Mix from AEO 2010 - 2030 Projections	2030	Gasoline , HEV, PHEV, Biodiesel and Ethanol with Included Alternate Feedstock, EV, PHEV	Biodiesel Hybrid, CNG, EV	Not considered
6	Baseline Case with Out-of-State Extraction Included	Same as 1				44.9

6.4.1. Baseline Case: Atlanta 2010 Conditions

As previously noted, the baseline scenario for this model pertains to present transportation and energy conditions for the Atlanta metro area. As there is no market share distribution available for Atlanta across all conventional and alternative vehicle propulsion technologies, national technology shares from the EPA's VISION model will be used as shown in the previous section. Electricity generation statistics are based on the previously-summarized values obtained from the Energy Information Administration's statewide electricity profile data, while road mileage data and classifications are based off of data provided by the Atlanta Regional Commission (Energy Information Administration, 2010; Atlanta Regional Commission, 2010).

Water consumption values for transportation and energy fuels will be based on existing production and extraction technologies as discussed in Chapter 3. In this case, region-specific water requirements for ethanol production are available and will be incorporated in this study (Wu et al, 2009). Furthermore, given that Georgia imports nearly all of its raw fuel materials for in-state consumption, extraction water consumption values are omitted from this baseline scenario as this case study is primarily focused on impacts on local water resources and not impacts from water resources outside of the region or the state. While there are multiple plant configurations (open-loop, cooling towers, cooling ponds, and air cooling), this baseline scenario will use water consumption values pertaining to power plants with cooling towers installed.

6.4.2. Case 2: Atlanta 2010 Conditions with Washington Electricity Mix and Seattle DVKT Values

A second case study reverts to the network conditions stated in the baseline case; however, with an intention to conduct a sensitivity analysis on electricity generation and its impacts on water consumption for transportation systems, the electricity generation mix for Washington is used. As such, there is a larger hydroelectric component in the electricity generation distribution to be considered in this model. Washington's electricity generation mix was selected primarily for its heavy reliance on renewable energy sources – especially that of hydroelectric power which constitutes 70.6 percent of its total electricity generation. As with Georgia, Washington imports all of its thermoelectric fuels from adjacent states or Canada and also uses significant amounts of biomass in its current electricity profile in addition to wind power. Otherwise, all of the other inputs as specified in the baseline case for 2010 conditions in Atlanta carry over to this sensitivity analysis.

Another input variable to be altered in this case is the daily vehicle kilometers traveled for the Seattle metropolitan area, which is at an average of 22 miles (35.2 kilometers) as opposed to the daily average of 27.9 miles (44.9 km). However, there are no concrete statistics on the number of automobiles or buses in use within the Seattle metro area, which inhibits the accuracy of this case study in terms of reflecting all transportation conditions in Seattle, so for this case existing vehicle numbers and shares as defined in the baseline case for Atlanta are used.

6.4.3. Case 3: Atlanta 2030 Conditions

The third scenario to be considered in this model uses 2030 projections for electricity generation along with vehicle market shares and efficiencies based on predicted increases from the Annual Energy Outlook 2010 and VISION models (Energy Information Administration, 2010; Maples et al, 2010). Additionally, this scenario also considers expansions in lane distance for highways, arterial roads, and collectors in the Atlanta metro area. Furthermore, it is assumed that there will be additional vehicle technologies such as plug-in hybrid and biodiesel powertrains as part of the automobile fleet in the network, while diesel hybrid buses will be included in the set of transportation modes as well. As with the baseline case for 2010, it is assumed that crude oil and natural gas are imported into and processed within Georgia, while biofuels are extracted and produced within the state. The same feedstock materials for ethanol and biodiesel will be used for this case study; as such, except for the addition of biodiesel into the fuel mix for this transportation system, fuel inputs are essentially the same as those of the 2010 case, meaning that the main driving factors for this study in terms of transportation modes are for vehicle efficiencies and electricity generation.

In this scenario, the electricity generation inputs are altered based on projections from the Annual Energy Outlook 2010 report for electricity profiles for the Southeastern U.S.. Changes made to water consumption components for power plant operation include assuming a boiler technology mix for coal-fired power plant generation to be that to 75% supercritical boilers and 25% subcritical boilers based on projections made by the National Energy Technology Laboratory (Gerdes et al, 2008). Otherwise, it is assumed that cooling towers are used for all other thermoelectric power plants.

The vehicle efficiencies and market share values in this scenario are projected to improve based on predictions made in the VISION model's base case (for the fuel efficiencies used in this model, 2030 efficiencies will use fewer liters per kilometer). As with the 2010 base case, national market share values are used, as region-specific vehicle distributions are not available. The number of vehicles is also expected to increase along with population growth; for buses, fleet increases are based on projections in Azevedo (2010) along with estimated bus technology shares. The total number of buses is projected to increase by approximately 26.3% while the number of passenger vehicles to be considered is expected to increase by 36.4% to 3,241,295 automobiles (Azevedo, 2010). For diesel vehicles, the 2030 case is assumed to implement biodiesel as an applicable fuel; diesel buses considered in this case are assumed to utilize hybrid powertrain components. DVKT values for automobiles and buses are to be the same as that of 2010.

6.4.4. Case 4: Atlanta 2030 Conditions with Washington Electricity Mix and Seattle DVKT Values

In addition to the above case profiles for 2010 conditions in Georgia and Washington, an altered 2030 case involving Washington State's electricity profile for Atlanta is also considered. The projected alterations in electricity output based on the Annual Energy Outlook 2010 for Washington are used in place of the projected energy profile for Georgia in 2030. Additionally, associated DVKT values for Seattle are used in place of daily travel distances for Atlanta as with the inputs for the Washington 2010 case. While there are modest increases in power plant generation for coal-fired sources, there are significant increases for nuclear and natural gas sources along with renewable energy sources that are assumed to apply to biomass, hydroelectric power, and solar power generation. However, as with the 2030 case for Atlanta, additional power plant technologies such as high-temperature nuclear reactors and supercritical coal-fired boilers will be implemented in this scenario.

6.4.5. Atlanta Case Study With Hypothetical Electricity Scenario and Alternative Fueled Vehicles: 2030 Conditions

While the first two scenarios for 2010 and projected 2030 network conditions for Atlanta were skewed towards conventional vehicle types and energy sources, the following case study will focus primarily on renewable energy sources and alternative vehicle configurations including CNG-powered vehicles, ethanol flex-fuel vehicles, plug-in hybrids, biodiesel hybrid vehicles, and battery electric vehicles for automobiles and CNG-powered vehicles for buses. For these transportation fuels, other feedstock or source materials will be considered; ethanol in this scenario will be produced either from corn feedstock or switchgrass (with production shares split halfway) while biodiesel will be produced either from soybeans or microalgae (also with an even production distribution). These inputs will be detailed along with the other fuel production inputs in the next section.

Several augmentations were also made to the electricity generation mix being considered for this case study. While there are still some thermoelectric generation components (such as coal-fired generation constituting 43% of the overall mix), the renewable energy shares in this assumed mix consists only of biomass, solar power, and wind power generation (hydroelectric power generation has been removed from this scenario). For thermoelectric power generation, even more water-efficient cooling technologies such as dry cooling configurations that use little to no water, along with to-be-implemented plant technologies such as integrated gasification combined cycle that converts coal into syngas for electricity generation. In addition to having lower greenhouse gas emissions compared to conventional coal-fired power plants, IGCC-based power plants also consume much less water. These emerging power plant technologies are implemented with projected electricity generation shares for all of the United States for 2030 as estimated in the Annual Energy Outlook 2010 report (Energy Information Administration, 2010). It is projected that 14 percent of the electricity generation mix is to be sourced from renewable energy sources; this estimate is assumed in this scenario to be evenly split between photovoltaic solar power and wind power. For electricity generation from liquid fuels (which constitutes 1 percent of total projected electricity generation), this scenario considers a halfway split between biodiesel and ethanol assuming the same fuel mixes previously described are also used for electricity generation.

6.4.6. Atlanta Case Study 2010 With Georgia Electricity Mix: Full Fuel Pathway Outlook

Up to now, these case studies have examined water consumption in transportation network usage with respect to local water resources assuming that fuel processing, transportation and distribution are allocated to local water resources. This case study will build upon the original baseline case and expand the scope of vehicle use-phase inputs by including water consumption requirements for fuel extraction for energy and transportation fuels imported into Georgia. As with all of the previous cases, either average values (if given) or low-end water consumption values (if data is given in terms of ranges) are used. Given that negligible amounts of water are consumed in the extraction of natural gas, water consumption values for natural gas and CNG are not altered (Gleick, 1994). For petroleum extraction, low-end water consumption values for the average of the three most dominant production regions in the United States are used

(Wu et al, 2009). The same additions are also included in water consumption inputs for electricity inputs. While inputs for natural gas are carried over from the 2010 baseline case, coal and uranium mining water consumption – in this scenario, it is assumed that uranium and coal are extracted from surface mines – will also be considered; for natural gas, there is negligible water consumption in onshore or offshore extraction (Gleick, 1994).

6.5. Scenario Inputs

The following section will detail the global and scenario-specific material and energy flow inputs for the considered transportation fuels and electricity sources, vehicle tank-to-wheel efficiencies and market share percentages, global flow inputs for the vehicles' auxiliary inputs and service infrastructural components, region-specific parameters for the network's road infrastructure along with global material and energy consumption inputs for road operation, as well as specified power plant and vehicle technologies for each scenario.

6.5.1. Fuel Production Inputs

Fuel production water consumption values for these scenarios were leveraged from Chapter 3; water consumption values for each fuel in terms of production process/step are summarized below in **Table 25**. For the first four scenarios, it is assumed that all fuels except for biofuels are extracted or mined outside of the region being assessed and thus extraction-related inputs are not considered; furthermore, only conventional biofuel feedstock such as corn for ethanol and soybeans for biodiesel will be assessed in these cases. Fuels derived from non-conventional mining sources such as

Canadian oil sands are also not included, and currently only U.S. fuel production is considered (i.e.: no foreign oil production) will be considered for these inputs.

Table 25. Fuel Production Water Consumption Inputs For Each Scenario.

Fuel Type	Energy Content, kWh/l	Extraction Water Consumed, l/l	Processing Water Consumed, l/l	Fuel Distribution Water Consumed, l/l	Fuel Storage Water Consumed, l/l
Conventional Sources for Fuels (All Cases)					
Gasoline	9.667	2.5-5.4 (2.5 is used)	1.088 (1-2.5)	0.65	---
Ethanol (Corn)	8.554	13.6 (Southeast)	3	Assumed to be same as gasoline	---
Switchgrass Ethanol	8.554	0.92 (Farm inputs only)	Same as corn ethanol		
Diesel	11.68	Same as gasoline			
CNG	9.667 (Equivalent Gasoline Volume)	0	0.209	0.104	50% compression by NG, 50% by electricity
Biodiesel (Soy)	10.94	12.2	1	0.65	---
Alternative Biofuel Feedstock (For Case 5: Hypothetical Scenario)					
Switchgrass Ethanol	8.554	0.92 (Farm inputs only)	Same as corn ethanol		
Biodiesel (microalgae, enclosed tubes)	10.94	20.1	Same as soy biodiesel		---

The last two scenarios in this case study expand on the conventional fuel inputs by considering alternative feedstock sources for biofuels – in this case, the addition of switchgrass and cellulosic material for ethanol and microalgae sources for biodiesel – as well as the inclusion of extraction-related water consumption inputs for gasoline and diesel. The alternative feedstock inputs are included in the hypothetical scenario for 2030, in which it is assumed that 50 percent of each of the biofuels being produced is sourced from each of these alternative sources. On the other hand, the extraction-included scenario focuses on conventional fuel production and sources while adding on water consumption values for fuel mining and extraction.

6.5.2. Electricity Generation Statistics

Monthly electricity generation statistics are available by state from the Department of Energy's Energy Information Administration State Energy Profile for Georgia and in its Annual Energy Outlook 2010 report, as well as in an annual basis from its Emissions & Generation Resource Integrated Database (eGRID) statistics (Environmental Protection Agency, 2010). Electricity generation types considered in these datasets include petroleum-fired electricity generation, nuclear power, natural gas-fired generation, aggregate coal-fired generation, hydroelectric power, as well as other renewable generation technologies such as solar, wind, and bioenergy generation. For 2030 conditions, the generation shares for these electricity generation types are expected to vary slightly due to population expansion, increases in energy consumption, or economic growth; the projected increases for each of these sources is obtained from estimates provided by the EIA's Annual Energy Outlook report for the southeastern and northwestern U.S. (Energy Information Administration, 2010). Electricity generation shares for the hypothetical 2030 share are based on U.S. average projections for 2030 using the same report; with biodiesel and ethanol plants representing liquid fuel-fired plant generation instead of oil-fired generation. The percentage shares for each scenario are summarized below in **Table 26**.

Table 26. Percentage Shares for Electricity Generation By Scenario.

Energy Source	Baseline Case	Washington 2010	Georgia 2030	Washington 2030	Hypothetical 2030
Thermoelectric Sources (Percent)					
Coal	50.4	7.9	47.7	6.76	43
NG	13.9	14.72	14.86	15.2	14
Liquid Fuel	0.082	0.052	0.047	0.035	0
Nuclear	31.1	10.558	33.12	10.37	17
Biomass Wood Waste	2.66	4.92	2.4	4.98	8.74e-3
Renewable Sources (Percent)					
Hydroelectric	1.91	60.2	1.76	61.1	0
PV Solar	0	0	0	0	7
Wind	0	1.57	0	1.59	7

Table 27 summarizes the distribution of electricity sources for Georgia for October 2010, where the majority of electricity production is derived from coal-fired sources with significant shares from natural gas and nuclear sources, as well as a sizable amount from hydroelectric power. In terms of other renewables, Georgia generates a sizable amount of electricity from wood waste and biomass but has no other significant renewable energy sources such as solar or wind power. While there certainly are significant fluctuations between electricity generation and consumption during the summer and that of winter, this generation distribution is consistent with annual electricity generation statistics from the eGRID model. This technology distribution is not projected to change significantly for 2030, although there are some slight increases in some sources such as nuclear power and combined cycle (NGCC) power production (in this model, NGCC will be used for natural gas-powered sources) (Energy Information Administration, 2010). In terms of water consumption, only local water usage will be considered, which includes water consumption for power plant cooling and operation and any water consumed in the transportation and processing of any associated fuels

(provided that they are processed or refined within Georgia, as with petroleum and natural gas).

Table 27. Current and Projected Georgia Electricity Generation Mix for 2010 and 2030 Based on Annual Energy Outlook 2010 Data (Energy Information Administration, 2010).

Electricity Generation Type	**Monthly Generation, GWh**	**2010-2030 Change, %**	***Projected Monthly Generation, GWh***
Petroleum-fired	8,000	-38.2	4946
Coal-fired	4,915,000	2.7	5,046,000
Nuclear	3,031,000	15.5	3,501,000
Natural Gas-Fired	1,356,000	15.85	1,571,000
Hydroelectric	186,000	0.48	186,892
Renewables (Biomass only)	259,000	0.48	260,241

In addition to assessing Atlanta's transportation network based on Georgia's statewide electricity profile, the statewide electricity profile from Washington for 2010 and 2030 conditions will also be considered. In contrast to Georgia's heavy dependence on fossil fuels for electricity generation – constituting approximately 70 percent of its total electricity generation resources – Washington's electricity profile is dominated by hydroelectric generation and also has smaller shares of coal-fired, natural-gas fired, and nuclear generation, as shown in **Table 28**. For Washington, petroleum is refined locally from imported crude oil, and natural gas is imported from Canada; similarly, coal is currently being imported from adjacent states (Energy Information Administration, 2010). For 2030 projected electricity generation, estimated increases are also obtained from the Annual Energy Outlook 2010 report based on reference cases for the northwestern region of the United States; natural gas combined cycle generation is expected to increase slightly while renewable sources will increase. As with Georgia, there is a sizable biomass share in terms of wood waste; however, Washington also has some amount of wind generation as part of its non-hydroelectric renewable portfolio (Energy Information Administration, 2010).

Table 28. Current and Projected Washington Electricity Generation Mix for 2010 and 2030 Based on Annual Energy Outlook 2010 Data (Energy Information Administration, 2010). Increases in renewable electricity generation are assumed to apply equally to all renewable sources.

Electricity Generation Type	**Monthly Generation, GWh**	**2010-2030 Change, %**	***Projected Monthly Generation, kWh***
Petroleum-fired	4,000	-38.16	3,185
Coal-fired	615,000	2.66	616,490
Nuclear	819,000	15.49	945,890
Natural Gas-Fired	1,142,000	15.85	1,384,500
Hydroelectric	4,674,000	19.2	5,570,000
Renewables (Solar (PV assumed))	125,250	19.2	145,280
Renewables (Biomass)	375,750	19.2	447,800

A quick inspection of these electricity generation distributions show that most of the current and projected scenarios place heavy emphasis on fossil fuels such as that of coal and natural gas or on hydroelectric power, with little consideration for other renewable sources such as additional forms of bioenergy and solar/wind power. This is where the hypothetical energy scenario comes in, as it focuses on a bioenergy and renewable energy distribution, with existing thermoelectric plants assumed to incorporate emerging water-efficient plant technologies while non-hydroelectric renewable sources such as solar and wind power will have larger shares. Additionally, a larger share of biofuels will be considered with implementations of alternative feedstock for biofuels such as microalgae for biodiesel and switchgrass or other cellulosic material for ethanol. This electricity mix distribution, based on annual electricity output, is shown below in **Table 29.**

Table 29. Projected Electricity Generation Values for National Electricity Mix in 2030 for Hypothetical Scenario. Oil-fired power generation has been replaced with equal shares of biofuel-powered plants. Renewable power generation is composed solely of solar and wind power for this scenario.

Electricity Generation Type	*Projected Yearly Generation, GWh*
Coal (IGCC Assumption)	2236
Natural Gas (NGCC Assumption)	728
Nuclear	884
Biodiesel	26
Ethanol	26
Wind	364
PV Solar	364
Renewables (Biomass)	0.454

6.5.3. Electricity Fuel and Plant Operation Inputs

The water consumption calculation for electricity generation in these scenarios includes both water consumption inputs from the production of thermoelectric fuels as well as water consumed in the operation of renewable and thermoelectric power plants. It is assumed that, as with the transportation fuel inputs in the previous sub-section, the water consumption values for fuel production carry over for all of the scenarios considered in this case study as these values are based on a national inventory of fuel production pathways; these values are summarized in **Table 30**. As with the fuel production inputs for the extraction-included scenario using 2010 conditions, water consumption for extraction will be added to the processing and distribution water consumption inputs used in all of the other scenarios; in this case, the pertinent values for fuel extraction are from petroleum recovery (adapted from transportation fuel inputs) as well as from coal and uranium mining (assumed to be from surface mines). For the hypothetical 2030 scenario, it is assumed that the coal is gasified for IGCC plants; as such, the coal production values are replaced with coal production values with gasification processing included. Furthermore, for the hypothetical scenario, biodiesel and ethanol are used instead of oil for liquid-fired power generation; it is assumed that each biofuel has an equal share of liquid fuel electricity shares for this scenario.

Table 30. Thermoelectric Fuel Inputs for This Case Study.

Source	Extraction Water Consumed, l/kWh	Process Water Consumed, l/kWh	Distribution Water Consumed, l/kWh	Reference
Coal	0.011	0.03	0.42	Fthenakis et al, 2010; Gleick, 1994
NG	0	0.057	0.03	
Petroleum	0.256	0.09	0	
Nuclear (Uranium)		0.132	0	
Coal for Gasification	0.011	0.156 (0.03 + 0.126)	0.42	
Biodiesel	1.292	0.106	0.069	Harto et al, 2010
Ethanol	2.31	0.509	0.1103	
Wood Waste (Biomass)	0	0	0	(Data Deficient)

While the thermoelectric fuel inputs are generally constant for both 2010 and 2030 conditions, there is more variation in water consumption inputs for power plant operation based on power plant technologies and environmental conditions. **Table 31** summarizes the power plant operation-related water consumption inputs, where for thermoelectric power plants it is assumed that cooling towers and existing plant configurations are used – for example, for coal-fired power plants it is assumed that subcritical boilers are used and for nuclear plants light water reactors (LWRs) are used. For renewable electricity generation, water consumption inputs for hydroelectric power plant generation vary depending on state, while biomass power plants are assumed to use steam plant configurations (Berndes, 2002). As shown in **Chapter 3**, water consumption inputs for solar and wind power is traced mainly to operation and maintenance.

Table 31. Power Plant Operation Inputs for 2010.

Source	Plant Configuration	Plant Water, l/kWh	Reference
Coal-Fired	Cooling Tower, Subcritical	2.6	Gleick, 1994
NG Combined-Cycle	Cooling Tower	1.02	Fthenakis et al, 2010
Oil-Fired	Oil Cooling Tower	0.61	Fthenakis et al, 2010
Nuclear	LWR	3.2	Gleick, 1994
Wood Waste Plant	Steam Plant	1.7	Berndes, 2002
PV Solar Farm	Central Utility Average	0.022	Harto et al, 2010
Wind Farm	U.S. Average	0.004	
Hydroelectric	GA Average	179.5	Torcellini et al, 2003
	WA Average	12.08	
	U.S. Average	17	Gleick, 1994

For scenarios in 2030 for Georgia and Washington, it is assumed that there will be more water-efficient (in terms of water consumption) power plant configurations to be implemented; however, these improvements are limited primarily to thermoelectric power plants as summarized below in **Table 32**. For coal-fired power plants, supercritical boilers are assumed to comprise 75 percent of all of the boilers used for these plants; for nuclear plants, it is assumed that HTGR plants are implemented (replacing light water reactors). For the hypothetical 2030 scenario, IGCC plants are used in place of conventional coal-fired power plants while dry cooling is used for NGCC and biomass/biofuel power plants.

Table 32. Power Plant Operation Inputs for 2030 State and Hypothetical Scenarios.

Source	Plant Configuration	Plant Water, l/kWh (2030 State Scenarios)	Plant Water, l/kWh (Hypothetical 2030 Scenario)	Reference
Coal-Fired	Cooling Tower, Supercritical-Subcritical Mix	0.937	----	Gleick, 1994
IGCC	Dry Cooling	----	0.655	

Table 32 (continued).

Source	Plant Configuration	Plant Water, l/kWh (2030 State Scenarios)	Plant Water, l/kWh (Hypothetical 2030 Scenario)	Reference
NG Combined-Cycle	Cooling Tower	1.02	0.0151	Gleick, 1994
Oil-Fired	Oil Cooling Tower	0.61	0.0151	Gleick, 1994
Nuclear	HTGR	2.2	2.2	Gleick, 1994
Ethanol/Biodiesel Plant	Dry Cooling	----	0	Fthenakis et al, 2010
Wood Waste Plant	Steam Plant (Hypothetical: Dry Cooling)	1.7	0	Berndes, 2002

6.5.4. Vehicle Inputs

Vehicle configurations for automobiles to be considered in these case studies include gasoline automobiles, compressed natural gas (CNG) automobiles, battery electric vehicles, ethanol-fueled vehicles, gasoline-powered hybrid electric vehicles (HEVs), gasoline-powered plug-in hybrid vehicles (PHEVs), ethanol-powered vehicles, and biodiesel-powered automobiles. Additionally, buses to be considered include clean diesel buses, biodiesel-fueled buses, ethanol-fueled buses, battery electric buses, and diesel-fueled hybrid-electric buses. For 2010 conditions, the distribution of public transit buses in Atlanta are primarily those of diesel-powered buses and CNG-fueled buses; as with automobiles, it is projected that more alternative bus configurations would be in use by 2030. The following sections detail specific inputs in terms of vehicle fleet efficiencies and market share values for each vehicle type and scenario; additionally, case study-specific inputs in terms of auxiliary fluids and servicing infrastructure will also be defined.

6.5.4.1. Vehicle Efficiency Input Parameters

Tank-to-wheel vehicle efficiency values (either in terms of fuel or energy efficiency) for each scenario are obtained from the Annual Energy Outlook 2010 report in terms of current fleet average efficiencies and projected increases in efficiency values for 2030. While standard fuel and energy efficiency values are not readily available for public transit buses, industry values for each bus configuration are substituted for this model (Weststart-CALSTART, 2006). For this case study, fuel efficiencies from the New Flyer D40LF standard bus (which is currently being implemented into MARTA's vehicle fleet) is used.

Table 33 summarizes the fuel efficiency values used for each unique scenario; for the last case where the baseline case includes extraction inputs; the 2010 vehicle efficiency values are re-used.

Table 33. 2010 and 2030 Efficiency Values for Passenger Vehicles and Buses (Energy Information Administration, 2010; Westart-CALSTART, 2006).

<table>
<tr><th>Vehicle Type</th><th>Baseline</th><th>Washington 2010</th><th>Georgia 2030</th><th>Washington 2030</th><th>Hypothetical 2030</th></tr>
<tr><td colspan="6">Autos (from Annual Energy Outlook 2010 and VISION model projections)</td></tr>
<tr><td>Gasoline IC</td><td colspan="2">0.0783 l/km</td><td colspan="2">0.062 l/km</td><td>0.0634 l/km</td></tr>
<tr><td>NGV</td><td colspan="2">0.0807 l/km</td><td colspan="2">0.063 l/km</td><td>0.0609 l/km</td></tr>
<tr><td>Gasoline HEV</td><td colspan="2">0.0544 l/km</td><td colspan="2">0.0427 l/km</td><td>0.0399 l/km</td></tr>
<tr><td>Battery EV</td><td colspan="2">0.295 kWh/km</td><td colspan="2">0.144 kWh/km</td><td>0.1266 l/km</td></tr>
<tr><td>PHEV-40</td><td colspan="2">Not considered</td><td colspan="2">0.0427 l/km (IC Mode)
0.249 kWh/km (EV)</td><td>0.0399 (IC)
0.249 (EV)</td></tr>
<tr><td>Ethanol</td><td colspan="2">0.0783 l/km</td><td colspan="2">0.0598 l/km</td><td>0.0637 l/km</td></tr>
<tr><td>Diesel</td><td colspan="2">Not Considered</td><td colspan="2">0.047 l/km</td><td>0.0542 l/km</td></tr>
<tr><td colspan="6">Buses (Data from survey of current buses and tied to buses used in MARTA)</td></tr>
<tr><td>Diesel</td><td colspan="2">0.5346 l/km</td><td colspan="3">Not considered</td></tr>
<tr><td>Diesel HEV</td><td colspan="2">0.4277 l/km (Not considered in 2010)</td><td colspan="3">0.326 l/km (Biodiesel used in hypothetical scenario)</td></tr>
<tr><td>CNG</td><td colspan="2">0.7841 l/km</td><td colspan="3">0.599 l/km</td></tr>
<tr><td>EV</td><td colspan="2">Not considered</td><td colspan="3">0.466 l/km</td></tr>
</table>

6.5.4.2. Vehicle Market Share Parameters

As market share values for each vehicle type for are not readily available for Atlanta – registered vehicle amounts for alternative fueled vehicles are available on a statewide level but are not separated by fuel type – the market share percentages for these vehicles are based on present-day national averages from the EPA's VISION Model (**Table 34**). For the buses used in this network case study fleet-specific DVKT values and market share numbers are based on transit data from the Metropolitan Atlanta Rapid Transit Authority (MARTA), the region's primary public transit operator. In following the model's scope in limiting transportation modes to automobiles and bus fleets, only the buses within MARTA's public transit system will be considered (MARTA, 2009). In addition to using national average market share percentages in 2010 and 2030 using Georgia and Washington conditions, he passenger vehicle and bus input parameters for this hypothetical scenario also specified. In this case, the majority of passenger vehicles to be considered in this network case are that of electric vehicles and CNG-powered vehicles at a market share of 25 and 30 percent, respectively. Plug-in hybrid vehicles, gasoline automobiles, and biofuel-powered vehicles (both ethanol and biodiesel) have 10 percent market share inputs each, while gasoline-powered HEVs have 5 percent. Bus fleet distributions for the hypothetical scenario will focus on alternative fuels, with CNG buses constituting 60 percent of the projected bus fleet and 20 percent each for biodiesel hybrid and electric buses. For diesel vehicles, the 2030 case is assumed to implement biodiesel as an applicable fuel; diesel buses considered in this case are assumed to utilize hybrid powertrain components.

While the Bureau of Transportation Statistics has passenger vehicle numbers on a state-by-state basis with 4,112,000 registered automobiles in Georgia as of 2009, city-specific numbers of Atlanta are not readily available. Using vehicle registration numbers allocated for the ten main counties in the Atlanta metropolitan area, it is assumed that there are 2,375,671 passenger vehicles within the network being considered as of 2009 (Georgia Department of Revenue, 2010). The number of vehicles is also expected to increase along with population growth; for buses, fleet increases are based on projections in Azevedo (2010) along with estimated bus technology shares. The total number of buses is projected to increase by approximately 26.3% while the number of passenger vehicles to be considered is expected to increase by 36.4% to 3,241,295 automobiles (Azevedo, 2010). For the hypothetical scenario, the total number of vehicles for each fleet is set at 2 million vehicles for automobiles and 700 vehicles for buses.

Table 34. Market Share Percentages for Each Scenario in terms of Vehicle Type.

<table>
<tr><th>Vehicle Type</th><th>Baseline</th><th>Washington 2010</th><th>Georgia 2030</th><th>Washington 2030</th><th>Hypothetical 2030</th></tr>
<tr><td colspan="6">Autos: 2010=2.375 million, 2030=3.3 million, 2030 Hypothetical=2 million</td></tr>
<tr><td>Gasoline IC</td><td colspan="2">90.84%</td><td colspan="2">55.27%</td><td>10%</td></tr>
<tr><td>NGV</td><td colspan="2">0.39%</td><td colspan="2">0.06%</td><td>30%</td></tr>
<tr><td>Gasoline HEV</td><td colspan="2">3.2%</td><td colspan="2">1.721%</td><td>5%</td></tr>
<tr><td>Battery EV</td><td colspan="2">0.01%</td><td colspan="2">0.15%</td><td>25%</td></tr>
<tr><td>PHEV-40</td><td colspan="2">Not considered</td><td colspan="2">16.433%</td><td>10%</td></tr>
<tr><td>Ethanol</td><td colspan="2">5.05%</td><td colspan="2">13.81%</td><td>10%</td></tr>
<tr><td>Diesel</td><td colspan="2">Not Considered</td><td colspan="2">6.268% (Biodiesel)</td><td>10%</td></tr>
<tr><td colspan="6">Buses: 2010=615, 2030=777, 2030 Hypothetical=700</td></tr>
<tr><td>Diesel</td><td colspan="2">26.1%</td><td colspan="2">Not considered</td><td>0%</td></tr>
<tr><td>Diesel HEV</td><td colspan="2">Not considered</td><td colspan="2">26.1% (Diesel)</td><td>20% (biodiesel)</td></tr>
<tr><td>CNG</td><td colspan="4">73.9%</td><td>60%</td></tr>
<tr><td>EV</td><td colspan="4">Not considered</td><td>20%</td></tr>
</table>

6.5.4.3. Global Parameters for Vehicle Auxiliary Flows

While vehicle efficiency and market share values are varied depending on year or scenario, this case study will assume that the auxiliary fluid inputs (engine or battery coolant mixtures and lubricants for IC powertrains) are the same for all scenarios – essentially, these parameters are global coefficients that are constant throughout for these scenarios.

While fuel efficiency values for automobiles and buses are readily available, fluid amounts for each type of vehicle are not as available. For passenger vehicles, it is assumed that the same amount of petroleum-based engine motor oil and lubricant are used for all internal combustion and CNG vehicles and that all vehicles for each fleet use the same mixture of ethylene glycol (antifreeze) and water for engine coolant. As there is limited information on average fleet auxiliary fluid amounts and service intervals, known auxiliary fluid parameters for certain vehicles will be used in place of actual average values. For IC vehicles, fluid amounts from the Ford Focus are used; auxiliary fluid amounts for buses are either provided by Weststart-CALSTART (2006) or scaled from automobile powertrains (**Tables 35 & 36**). Similarly, service intervals are assumed to be 7500 miles (12,000 km) for replacing engine lubricants and 30,000 miles (48,000 km) for coolant flushes.

Table 35. Assumed Fluid Amounts for Passenger Vehicles by Technology Type.

Vehicle Technology Type	Lubricant Amount, l	Service Interval, km	Coolant Antifreeze Amt, l	Coolant Water Amt, l	Service Interval, km
Internal Combustion	3.7854	12,000	2.7	2.7	48,000
Electric Vehicles	n/a	n/a	2.7	2.7	48,000
PHEV	3.7854	12,000	2.7	2.7	48,000

Table 36. Assumed Fluid Amounts for Buses by Technology Type.

Vehicle Technology Type	Lubricant Amount, l	Service Interval, km	Coolant Antifreeze Amt, l	Coolant Water Amt, l	Service Interval, km
Internal Combustion	27.958	12,000	2.7	2.7	48,000
Electric Vehicles	n/a	n/a	2.7	2.7	48,000

6.5.5. Road Infrastructure Inputs

Much of the data regarding material and energy flows for road infrastructure usage have been sourced from the Ecoinvent life cycle database and Spielmann et al (2007) based on life cycle inventories for road networks in Switzerland based on construction and resurfacing/renewal, normal operation inputs and emissions, and road disposal. As such, the material and energy inputs for these roads are purely based on Swiss conditions, although material and energy expenditures for road operation and maintenance in the United States are not readily available. Thus, for this model, it is assumed that Atlanta and all other major regions in the United States have the same set of inputs and equivalent amounts of material and energy expenditures for its roads. While material and energy inputs are also included for the construction and operation of other infrastructural components such as tunnels and bridges, these components are not considered in the case studies for this model. The material and energy inputs for these roads, separated by road type, are summarized below in **Table 37** for material and **Table 38** for energy flow inputs.

Table 37. Material Inputs for Road Operation and Maintenance By Road Type (Spielmann et al, 2007).

Material Flow	Annual Motorway Material Consumption, kg/km	Annual Class 1 Road (Arterial) Material Consumption, kg/km	Annual Class 2 Road (Collector) Material Consumption, kg/km	Material Water Consumption Intensity, L/kg
De-icing Salt	22.8	6	1.67	38.2
Paint	0.00517	0.00864	0.02609	18.764

Table 38. Energy Inputs for Road Operation and Maintenance by Road Type (Spielmann et al, 2007).

Energy Flow Type	Annual Motorway Consumption, kWh/km	Annual Class 1 Road Consumption, kWh/km	Annual Class 2 Road Consumption, kWh/km
Grid Electricity	2.73E-02	2.94E-03	6.04E-04
Fuel	0.053184	0.016668	0.009141

It was previously discussed that while electricity and fuel inputs for road maintenance and operation are assumed to be consistent throughout each classification of roads, some operational inputs such as de-icing material inputs are seasonal and are only applicable to wintry or freezing conditions; that said, material consumption for these seasonal materials are calculated on a yearly basis and are assumed to account for skewed inputs. However, as these inputs, along with energy and other expenditures for these roads, are converted to daily consumption values it is important to note that these material inputs for this model are not necessarily accurate for a daily basis as the daily average consumption is not weighted. As with road renewal inputs, these inputs can be modified to account for seasonal variations or omitted altogether should more accurate life cycle inputs for specific regions in the United States are available.

Road mileage data and energy-related water consumption inputs for road operation and maintenance, however, are representative either of regional or national conditions. Road lane mileage for this model is available from local transportation agencies – in the case of Atlanta's roads, lane mileage is available for 2010 and 2030 projections from the Atlanta Regional Commission based on its Envision6 Regional Transportation Plan, while county-based lane mileage is available from the Georgia Department of Transportation – albeit with a less concrete classification of public and private roads. For these case studies, data from the Atlanta Regional Commission is used.

The road mileage/distance data available from the Atlanta Regional Commission is allocated based on road classifications used, which in this case pertains to interstates/highways, arterial roads, and collector roads. Road mileage data for 2010 and projected mileage data for 2030 by road classification is shown below in **Table 39**. Given that these classifications are not the same as those used in the life cycle inventories for Spielmann et al (2007), it is assumed that material input and energy input data for motorways corresponds to those of interstate freeways and highways while arterial roads correspond to Class 1 roads and collectors correspond to Class 2 roads in terms of material and energy inputs.

Table 39. Aggregate Road Lane Mileage By Road Type for the Atlanta Metro Area (Atlanta Regional Commission, 2010).

Road Type	2010 Lane Miles	2030 Lane km	2030 Expansion Miles	2030 Expansion km	2030 mileage	2030 km
Interstate and Freeway	2938	4700.8	241	385.6	3179	5086.4
Arterials - Principal	2424	3878.4	475	760	2899	4638.4
Arterials - Minor	6274	10038.4	1456	2329.6	7730	12368
Collector	5311	8497.6	232	371.2	5543	8868.8

6.6. Discussion: System Boundary and Additional Assumptions

Presented in the above sections are the global and scenario-specific input parameters in terms of electricity generation and fuel production, vehicle efficiency and market share percentages for the automobile and bus fleets in this network, along with material and energy consumption values for the road and vehicle servicing infrastructure in this transportation system. All of the above inputs, with the exception of the sensitivity analysis parameters including fuel extraction, are based either on the global assumption that these values pertain to consumption from local water resources. Furthermore, with the exception of a few water consumption inputs for fuel production and hydroelectric power and vehicle travel parameters, material and energy inputs along with associated water consumption requirements are not necessarily available on a regional basis. Thus, material and energy flow data are based on national averages unless more spatially explicit data for the Atlanta region is available.

As hinted in the initial definition of the scope for this model, the fuels to be assessed in these case studies will include petroleum-based fuels (gasoline for automobiles and diesel for buses), compressed natural gas, ethanol, biodiesel, and locally generated electricity. That said, it is important to note that not all of these fuels are produced locally, as Georgia has no petroleum reserves and imports almost all of its current set of transportation and energy fuels from adjacent states or from foreign sources (Energy Information Administration, 2010). In the baseline, real world-based case study for 2010 conditions for Atlanta, it is assumed that all fossil and thermoelectric fuels applicable to the electricity generation or transportation sector – with the exception of municipal solid waste or wood waste – is extracted from out-of-state sources and processed in-state via processing plants or refineries within Georgia. That said, it is assumed for these case studies that projected alternative transportation and energy fuels such as biodiesel and ethanol would be produced locally, as it has been suggested that there may be a feasible implementation of these biofuels given that these fuels can be produced from existing crops in Georgia. It is also assumed that for the implementation of these biofuels additional processing facilities would have to be constructed locally; thus, water consumption from the construction of these production plants would be within the scope of this model.

It is assumed that the processing plants and distribution networks for transportation and energy fuels within this model and for Atlanta are representative of those in average fuel pathways across the United States; as such, national water consumption values for the processing and transportation of these fuels is used. For biofuels, national water consumption values for crop irrigation are used, unless if regional irrigation requirements are available. It is also assumed that biofuels and petroleum-based transportation fuels would use similar distribution networks and thus have equivalent water consumption values traced to fuel transportation (Harto et al, 2010).

Based on these characteristics and assumptions for fuel pathways in Georgia, the case study will omit any water consumption pertaining to fuel extraction *unless* if the fuel is extracted within Georgia, while water consumption factors pertaining to fuel processing will be applicable to all fuels as these transportation and energy fuels are passed through processing plants and refineries within the state (Energy Information Administration, 2010). This is not to say that water consumption related to extraction is unimportant or negligible for the entire fuel production life cycle, considering that secondary and tertiary recovery operations for some transportation fuels consume significant amounts of water (Wu et al, 2009; Gleick, 1994); however, given that the assessment is constrained to examining impacts on local water resources in sustaining a transportation network's usage, it is assumed that the water consumed for imported raw fuel materials is associated with other regions. Furthermore, while the water consumption elements for imported fuels may exclude extraction values in this particular region, it may be included in this model for other regions where fuels are procured locally within those regions. As part of the set of sensitivity analyses in these scenarios, all water consumption components for imported fuels will be considered in order to present a more comprehensive outlook of water flows in the transportation fuel's life cycle with respect to a transportation network's usage.

All of these parameter input specifications will ultimately be used to calculate total network-level and domain-level water consumption estimates for a given day within the Atlanta transportation network based on the above set of scenarios. The next chapter will outline these results and overall trends in transportation-related water consumption.

CHAPTER 7

CASE STUDIES: RESULTS AND DISCUSSION

7.1. Overview

This chapter continues the discussion on outlining the scenarios to be considered in the Atlanta case study for this transportation network system model in terms of overall conditions and associated inputs for vehicle-specific parameters, fuel production and electricity generation parameters, as well as global parameters for road and vehicle servicing infrastructure within this network. The following sections begin with applying these aforementioned inputs to the model and examines the calculated water consumption amounts on a network, domain, and component level across all of the six scenarios – along with direct comparisons for each level across any unique cases such as in terms of 2010 versus 2030 conditions or between state electricity profiles. This chapter will then close with a multi-level discussion on overall trends and shortcomings for each group of elements in this transportation network model along with a four-step validation process intended to assess the quality of the model results and applicability to transportation planning and associated decision-making processes.

7.2. Daily Network Water Consumption Results

The overall daily network water consumption results for each of the six scenarios are summarized below in **Figure 88** and **Table 40** in terms of total automobile fleet water consumption for a given DVKT value (44.9 km/day using Atlanta's travel conditions, 35.2km/day using Seattle's travel inputs), daily bus fleet usage water consumption, road infrastructure water consumption, and vehicle servicing usage water consumption. As seen in the comparison chart, the vast majority of water consumption for a given day in these scenarios can be traced either to automobile fleet or vehicle infrastructure usage, while bus usage and road infrastructure water consumption constitutes a very small portion of the overall value. For the 2030 scenarios involving Georgia and Washington State's electricity generation profiles, the increased usage of plug-in hybrid vehicles and biofuel-powered vehicles results in a significantly higher water consumption value due to the high water consumption values from electricity generation; these water consumption trends for electricity generation will be discussed in more detail in the next section.

In addition to the above scenarios, the network-level water consumption values for the baseline case with included fuel extraction and mining inputs shows that including such water consumption from the entire fuel production pathway doubles automobile usage water consumption primarily due to the water-intensive nature of oil recovery and ultimately increases total network water consumption by 91 percent to 40.6 million liters per day. As the hypothetical scenario focused primarily on vehicle usage water consumption, the overall values for these two analyses are not included in this comparison.

At this time, only water consumption based on vehicle usage (based on fuel/energy consumption and auxiliary fluid usage) and road infrastructure operation are considered for the network-level scenario results. **Section 7.7** will address the impacts of vehicle maintenance (servicing and washing in this model and system) on total water consumption and discuss any potential inconsistencies in input parameters, while **Section 7.8** considers overall water usage for electricity generation and fuel production and how they impact individual vehicle use-phase results.

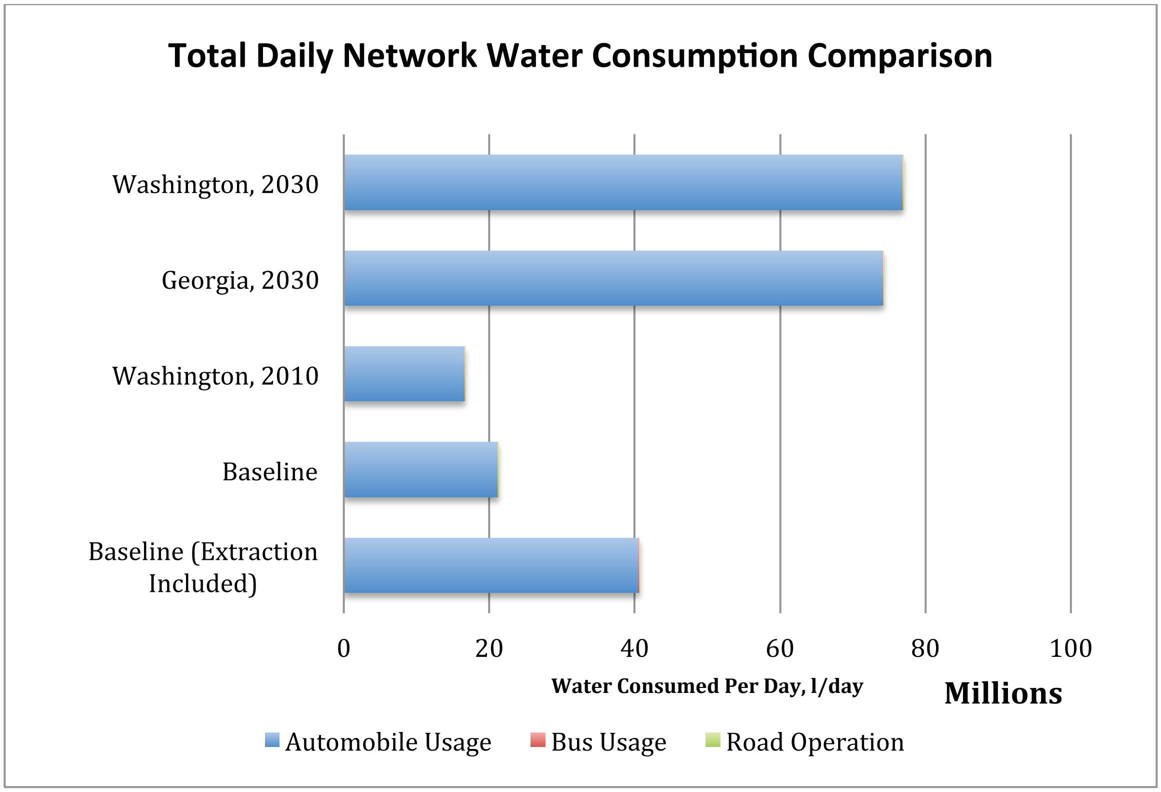


Figure 88. Comparison of Network-Level Water Consumption Results by Scenario Without Servicing Inputs (Hypothetical Scenario Not Considered).

Table 40. Rounded Network-Level Water Consumption Values By Scenario (Hypothetical Scenario Not Considered).

	Automobile Usage	Bus Usage	Road Operation	Total Water Consumption, l/day
Baseline (Atlanta/ Georgia, 2010)	21,110,000	80,034	21,462	21,210,580
Baseline (Extraction Included)	40,526,800	99,525	21,463	40,647,790
Washington, 2010	16,554,880	80,380	21,463	16,656,720
Georgia, 2030	74,133,130	67,040	24,390	74,224,560
Washington, 2030	76,815,400	83,560	21,461	76,899,000

Network-level water consumption values for these cases can be measured in the millions of liters per day, although based on overall regional water usage values for Atlanta in 2010 – approximately 2.27 billion liters per day – the Georgia 2010 and 2030 scenario water consumption values of 54.75 and 110 million liters per day are comparatively small (Metropolitan North Georgia Water Planning District, 2010; **Figure 89**). However, this is not an appropriate comparison with local water resources as water consumption is generally a small portion of water usage; had daily water usage values been considered for this model, the percentage of water usage allocated to transportation network operation would be much greater.

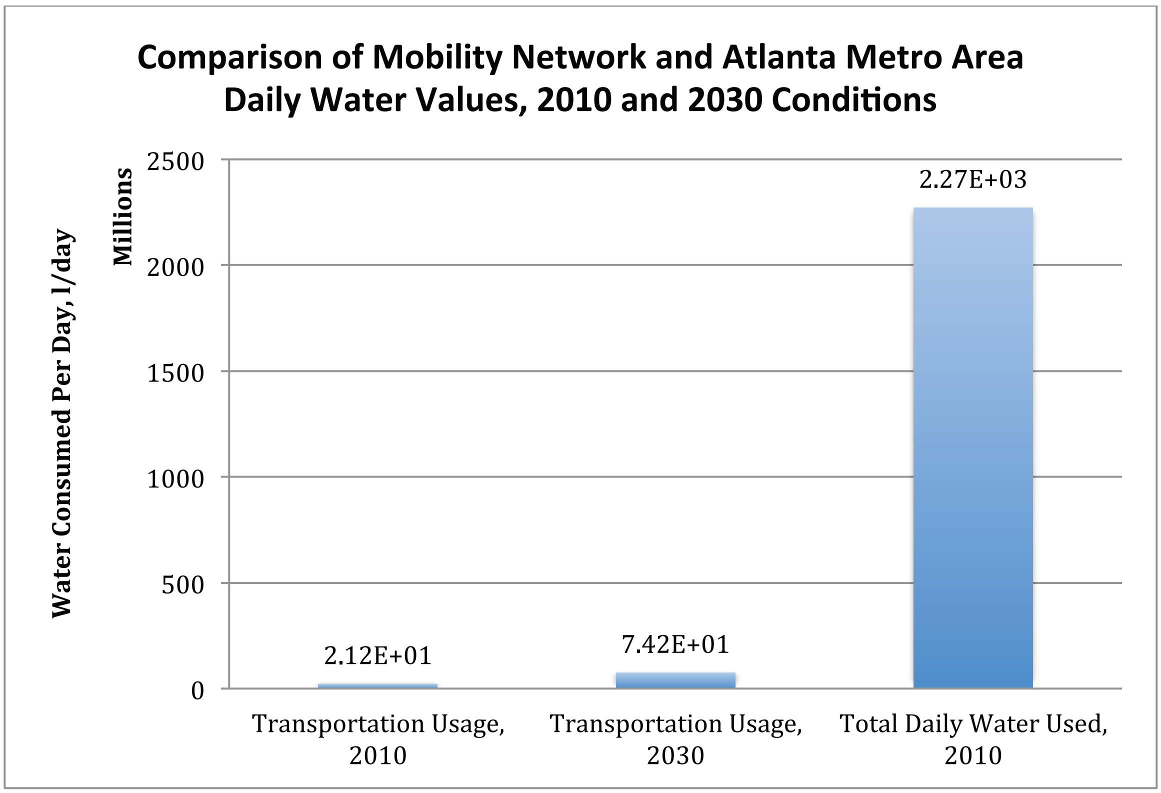


Figure 89. Comparison of Network Water Consumption and Total Daily Water Usage in Atlanta, 2010 and 2030 Conditions.

7.3. Electricity Generation Water Consumption Results

The previous chapter outlined individual energy outputs for each thermoelectric and renewable electricity generation sources in addition with thermoelectric fuel production inputs. Applying these parameters to the model's analysis framework through each scenario yields the normalized water consumption values for each electricity generation mix considered in this case study as shown below in **Figure 90**. Based on these calculations, the hydroelectricity-dominated Washington State electricity mix has the highest average values at 8.6 to 8.82 liters per kWh for 2030 and 2010, respectively; despite the relatively low evaporation rate for Washington compared to that of Georgia, the heavy dependency on hydroelectric power for Washington offsets any reductions in water consumption. On the other extreme, the dry cooling and non-hydroelectric electricity mix in the hypothetical 2030 scenario results in a low water consumption value of 1.237 l/kWh. The next few subsections will detail a breakdown of electricity consumption by technology and profile distribution across all scenarios.

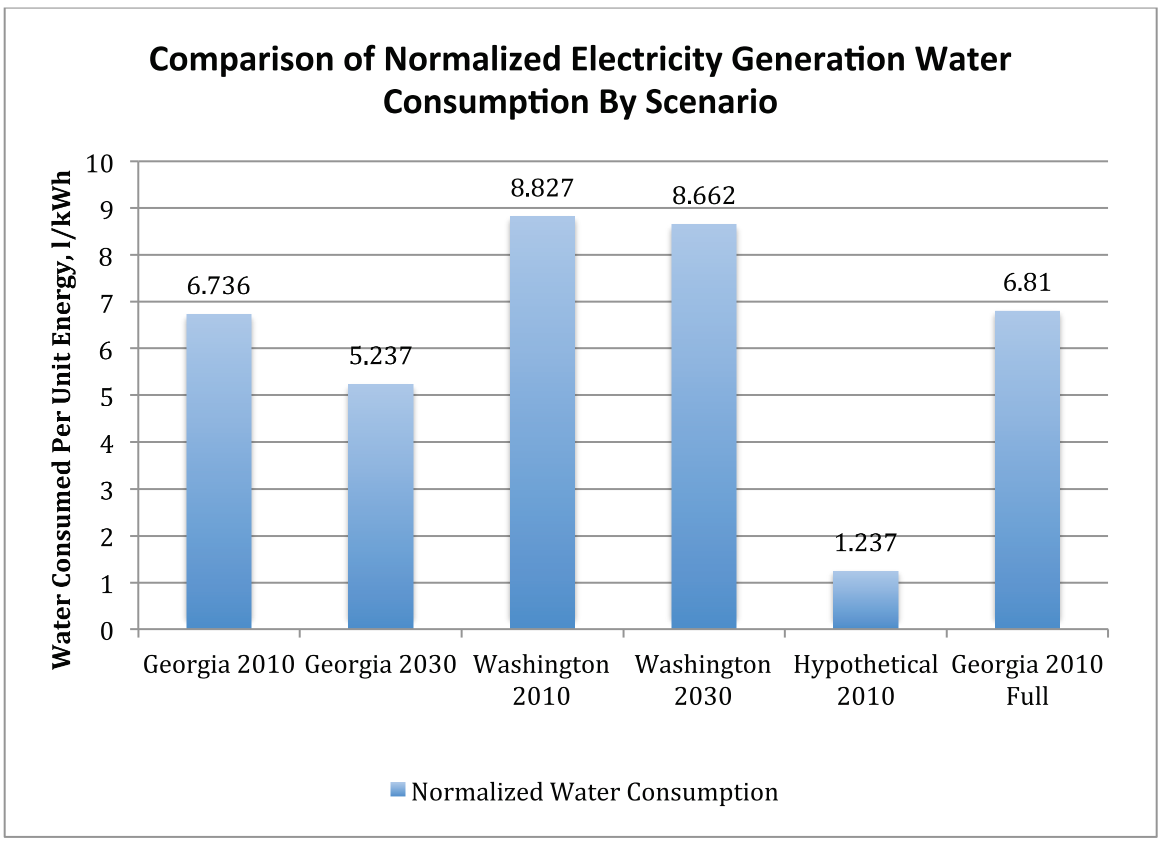


Figure 90. Comparison of Normalized Electricity Distribution Values By Scenario.

7.3.1. Water Consumption Breakdown for Electricity Generation

7.3.1.1. Georgia Electricity Mix for 2010 Conditions: Baseline and Extraction-Included

Water consumption rates for each electricity generation source using 2010 assumptions for Georgia can be summarized below in **Figure 91** in terms of plant operation and thermoelectric fuel production water consumption. Hydroelectric power generation by far consumes the most water due to evaporative losses in hydroelectric reservoirs at 179.5 liters per kilowatt-hour, while oil-fired generation using cooling towers consumed the least amount of water at 0.7 l/kWh for fuel production and electricity generation. Natural Gas Combined Cycle generation (NGCC) consumes the second-least amount of water at 1.107 l/kWh when incorporating cooling towers, while light water-based nuclear power and coal-fired generation consume the most water among all thermoelectric power sources at 3.33 l/kWh and 3.05 l/kWh, respectively. Since Georgia imports the raw fuel materials needed for thermoelectric power generation and that extraction-based water consumption is omitted from the scope of this case study, power plant direct water inputs dominate electricity generation water consumption in Georgia in 2010. It should be noted that these water consumption factors are based on conventional technologies such as light water reactors and subcritical boilers; more water-efficient power plant configurations are slated to be introduced later in the future and will be considered in the 2030-based scenarios.

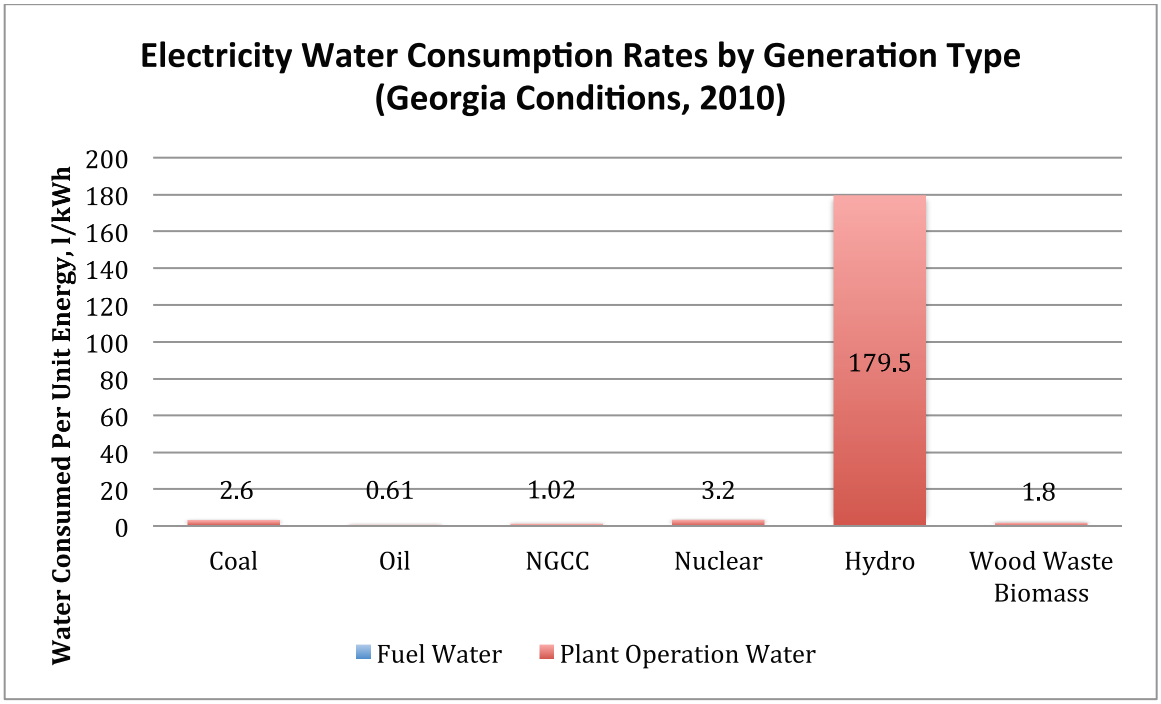


Figure 91. Normalized Water Consumption Rates for Georgia Electricity Generation, 2010 Conditions (Baseline Case).

Table 41. Fuel Production and Plant Operation Water Consumption Results (Georgia Electricity Mix, 2010).

Electricity Source	Fuel Water, l/kWh	Plant Operation Water, l/kWh
Coal	0.45	2.6
Oil	0.09	0.61
NGCC	0.087	1.02
Nuclear	0.132	3.2
Hydro	0	179.5
Wood Waste Biomass	0	1.8

The water consumption trends for electricity generation are slightly different when looking at an aggregate level. When considering total energy output from each source in addition to the above water consumption rates, a sizable portion of water consumption for electricity generation is traced to total water consumption for thermoelectric power generation, which is expected considering that thermoelectric power generation has the largest water consumption share in Georgia year by year

(**Figure 92**). Given that coal-fired power generation constitutes approximately 65% of power generation in Georgia in 2010, aggregate water consumption for coal-fired electricity production is the largest water consumption component in Georgia's electricity mix with 13.5 billion liters of water consumed per month. Nuclear power generation has the third-largest aggregate water consumption at 9.98 billion liters of water per month – although the nuclear generation sector has the largest water consumption rate among all thermoelectric sources, it provides only about a quarter of the state's generated electricity. Despite a somewhat low energy output share for hydroelectric power, this generation source has the highest aggregate water consumption at 33 billion gallons of water. It should be noted that this high water consumption figure from evaporative losses are not necessarily solely traceable to power generation, as hydroelectric dams are also used for flood control and diverting water for other uses (Torcellini et al, 2003); however, as hydroelectric dams require these reservoirs for continued operation, this consumption figure can be assumed to be primarily traced to electricity generation. While oil-fired power generation consumes the least total water per month, this is due to that oil-fired power generation represents 0.7 percent to total monthly electricity generation and that oil-fired power plants use the least amount of water based on values provided by Fthenakis et al (2010). While wood waste power generation has a similarly low amount of total water consumption at 466 million liters per month, it is assumed that no direct water input is needed for wood waste.

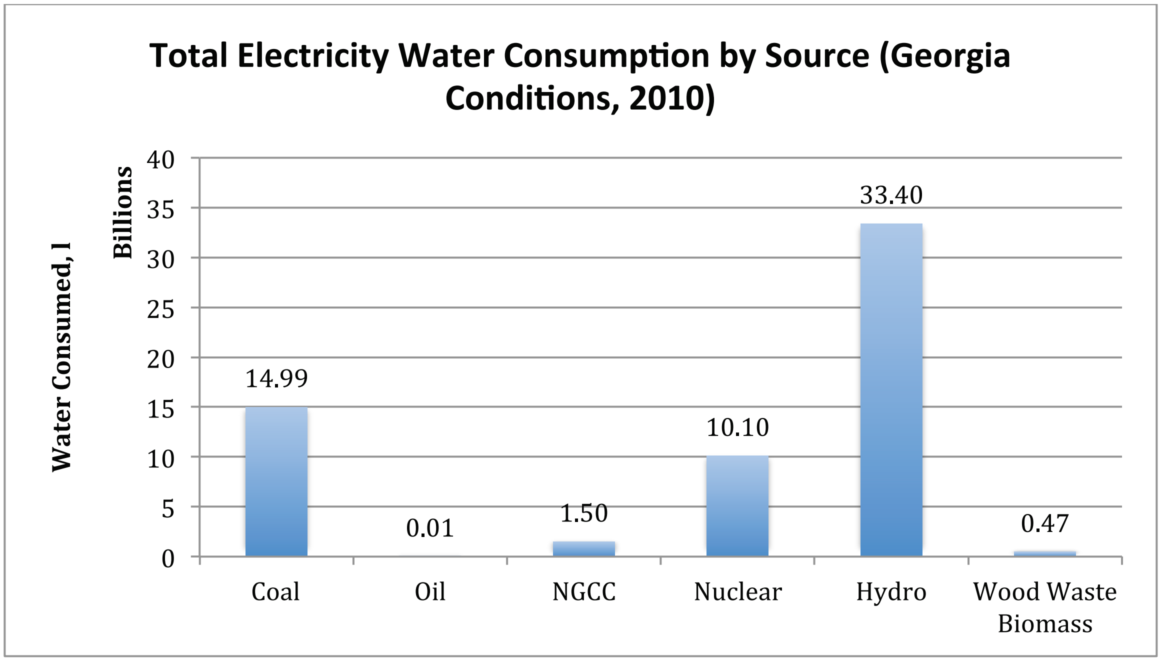


Figure 92. Total Monthly Electricity Generation Water Consumption by Source in Georgia.

As the above water consumption rates are based on the assumption that all of the fuels used in this mix are not extracted within the state or local region, extraction-related water consumption values for thermoelectric fuel production are included as one of the additional scenarios in this case study; a comparison of baseline thermoelectric fuel production values and extraction-included values is shown in **Figure 93**. While the inclusion of coal surface mining does not significantly affect fuel production water consumption for coal-fired power plants and while natural gas extraction consumes negligible amounts of water, including extraction-related values for oil recovery and surface mining for uranium significantly affects fuel water values for these sources – in particular, uranium mining increases fuel production water consumption twofold while oil recovery adds 3 times that of the baseline oil water value to overall fuel production water consumption. That said, while oil-fired power plant generation constitutes a very small percentage of Georgia's electricity mix, nuclear power produces 31 percent of the state's monthly electricity output. In the case for petroleum production, this illustrates the previous observations discussed in Chapter 2 that petroleum recovery is very water-intensive due to additional recovery methods that directly or indirect inject water to retrieve more crude oil from wells that are being used today. While water consumption from power plant operation is still the dominant water consumption component for thermoelectric power generation, fuel-related water consumption in this scenario constitutes a larger percentage of each source's overall water consumption rate. Examining aggregate values for monthly electricity generation, however, shows that including fuel extraction results in a relatively minuscule increase in water consumption, with normalized water consumption for this scenario at 6.81 l/kWh versus 6.75 l/kWh for the baseline case (**Figure 94**).

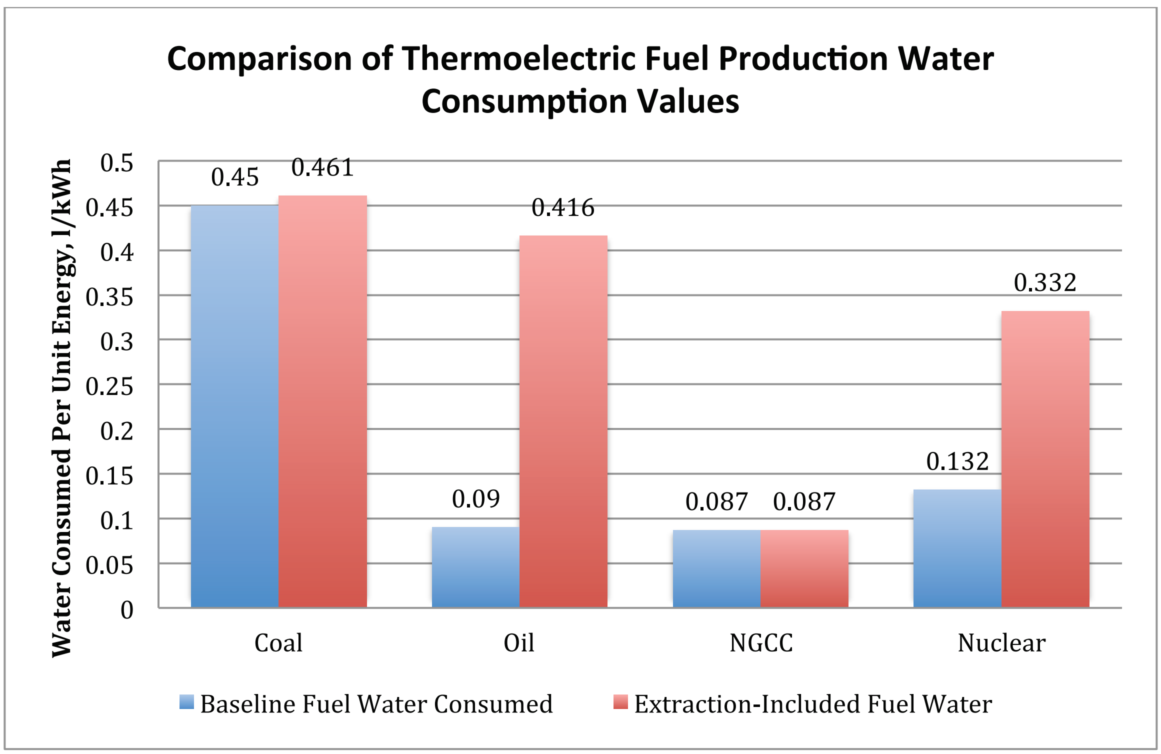


Figure 93. Comparison of Thermoelectric Fuel Production Water Consumption Between Baseline and Extraction-Included Scenarios.

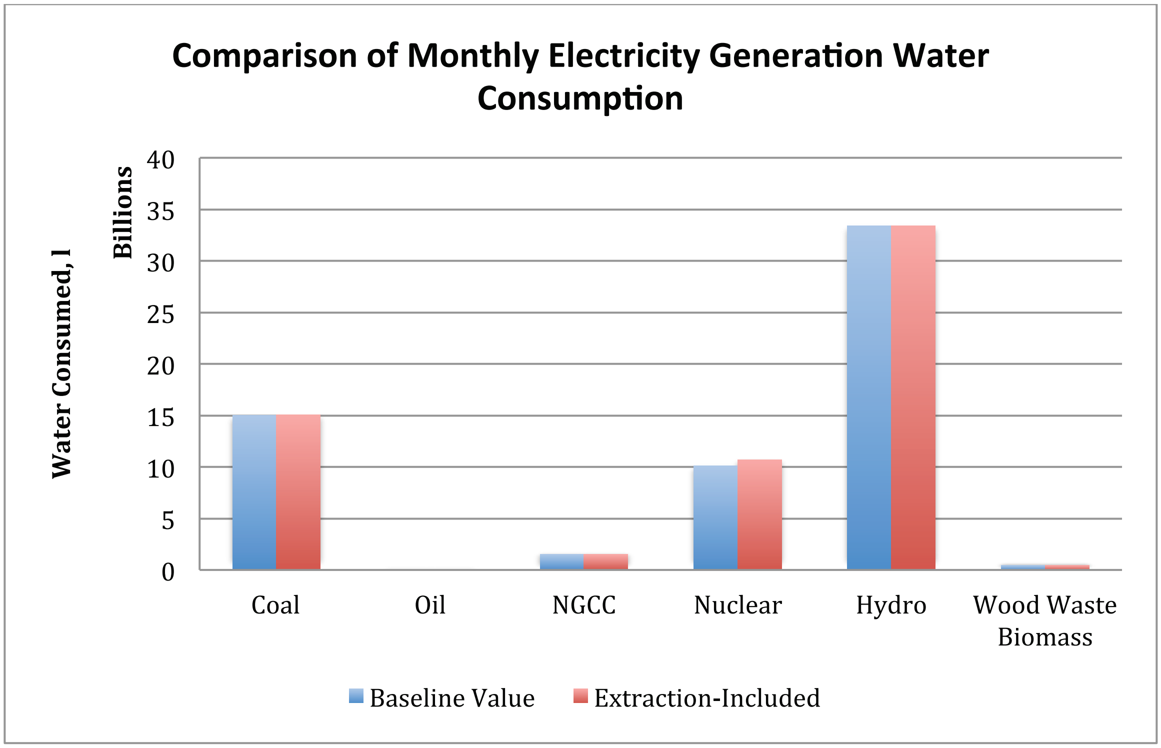


Figure 94. Comparison of Monthly Electricity Generation Water Consumption Between Baseline and Extraction-Included Scenarios.

7.3.1.2. Georgia Electricity Mix for 2030 Conditions

The normalized water consumption rates for plant operation and fuel production for electricity generation based on fuel conditions in Georgia for 2030 are summarized below in **Figure 95** by generation type. As before, water consumption rates for hydroelectric power generation in Georgia are the highest among all power generation sources considered; however, among all other sources water consumption rates are lower in 2030 due to implementing more water-efficient plant configurations. For example, HTGR (High-Temperature Gas Reactor) nuclear plants consume 2.2 liters of water per kilowatt-hour compared to 3.2 for the light-water reactors considered for the baseline case; similarly, water consumption rates for coal-fired power generation are lower at 0.93 liters of water per kilowatt-hour based on the subcritical-supercritical boiler mix for cooling tower-based plants previously discussed. Water consumption for oil-fired power plants is still the lowest at 0.61 liters of water per kilowatt-hour, with all other sources at the same water consumption rates as that of 2010 conditions.

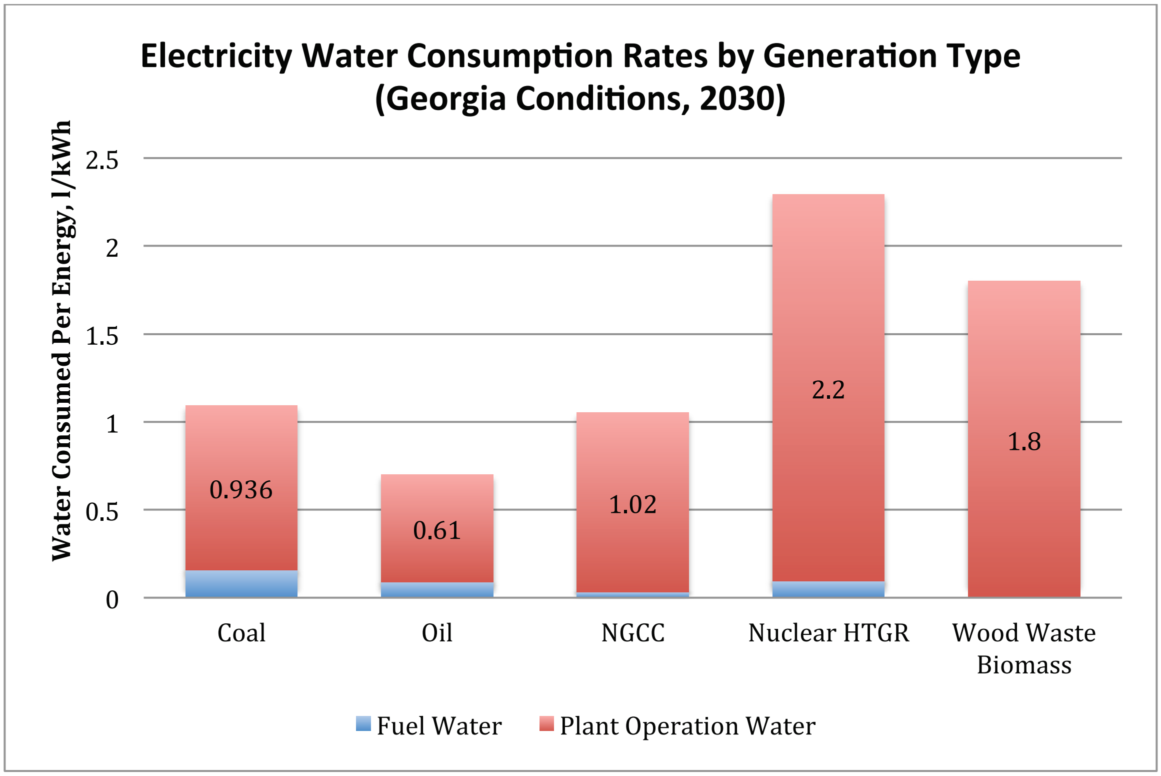


Figure 95. Normalized Water Consumption Rates for Georgia Electricity Generation, 2030 Conditions (Hydroelectric Water Consumption Not Included).

Aggregate water consumption values for electricity generation have similar trends as that of Georgia's electricity mix in 2010, with total monthly water consumption from hydroelectric power the largest component amongst all sources considered (**Figure 96**). Compared to the electricity generation water consumption results for the 2010 base case, total hydroelectric power water consumption from reservoir evaporation 2030 is marginally greater due to a modest projected increase in hydroelectric power shares as estimated by the Annual Energy Outlook 2010 report. Given the more water-efficient power plant configuration for coal-fired power generation, water consumption for coal-fired power generation is lower at 5.524 billion liters per month in 2030 compared to 13.6

billion liters per month in 2010 despite a 7 percent increase in coal-fired generation output. In contrast to the results for the 2010 baseline case, nuclear power water consumption has the largest monthly water consumption among all thermoelectric sources, although the monthly estimate of 8 billion liters in 2030 is less than the approximately 10 billion liters consumed in 2010 due to the substitution of HTGR technologies in place of light water reactor configurations. On the other hand, wood waste power generation and natural gas power water consumption are marginally more in 2030 mainly due to an estimated small increase in output based on AEO projections.

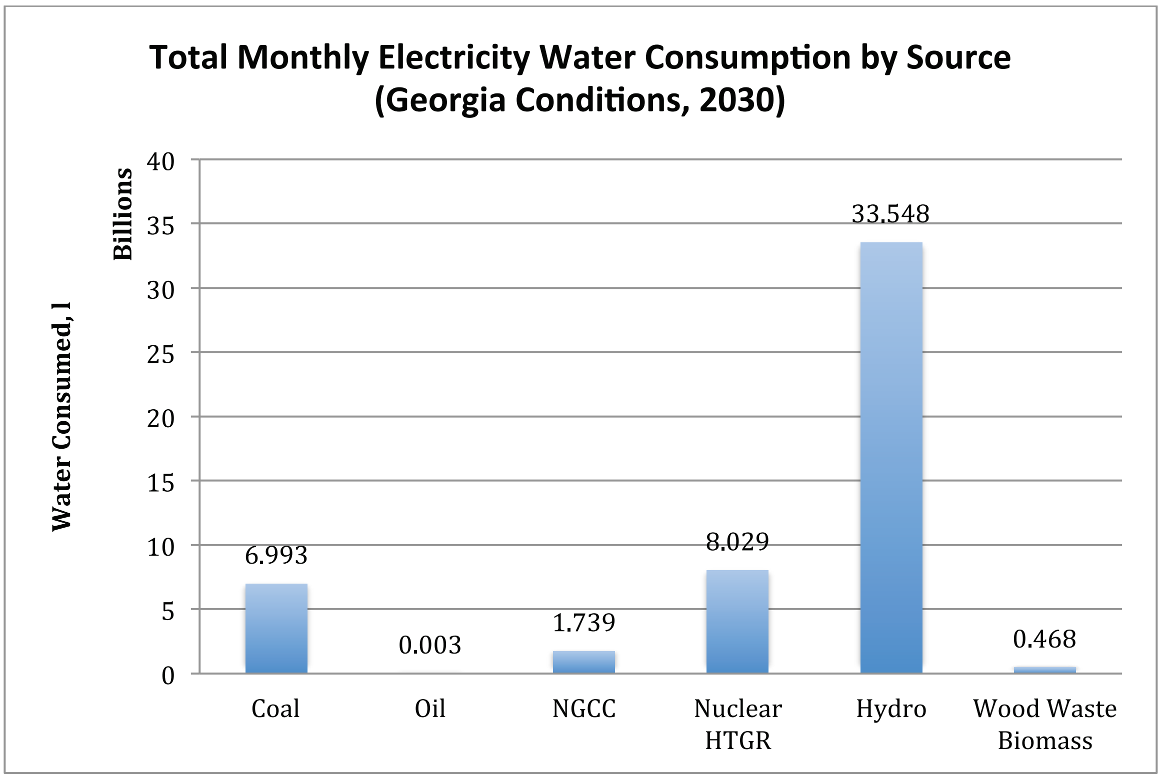


Figure 96. Total Monthly Electricity Water Consumption for Georgia Electricity Mix in 2030 Conditions.

Ultimately, 15.7 billion liters of water are consumed for thermoelectric power generation an 33.5 billion gallons for one month, which at face value illustrates a significantly lower overall thermoelectric generation water consumption value compared to 25.4 billion liters per month in 2010; on the other hand, renewable water consumption has marginally increased from 2010 to 2030 assuming that the evaporative losses from hydroelectric power are the same for both cases. The reduced thermoelectric water consumption results in a normalized average water consumption value of **5.24 l/kWh**, meaning that improvements in thermoelectric power plant technologies ultimately yield a 22 percent decrease in average electricity generation water consumption for Georgia in 2030.

7.3.1.3. Washington Electricity Mix for 2010 Conditions

Applying Washington State's electricity mix for 2010 yields the normalized water consumption rates for fuel production and plant operation based on present conditions in Washington are summarized below in **Figure 97**. As the plant operation inputs for electricity generation are based on national averages, there is little to no variation with respect to thermoelectric power generation. That said, the water consumption rate for hydroelectric power is significantly less for Washington at 12.075 liters per kilowatt-hour – in the case of this difference between Georgia and Washington, the slightly hotter climate of Georgia may lend to its significantly higher evaporative losses for hydroelectric power (Torcellini et al, 2003). As with Georgia's electricity grid, water consumed in the processing and distribution of energy fuels constitutes a very small component of electricity generation water consumption.

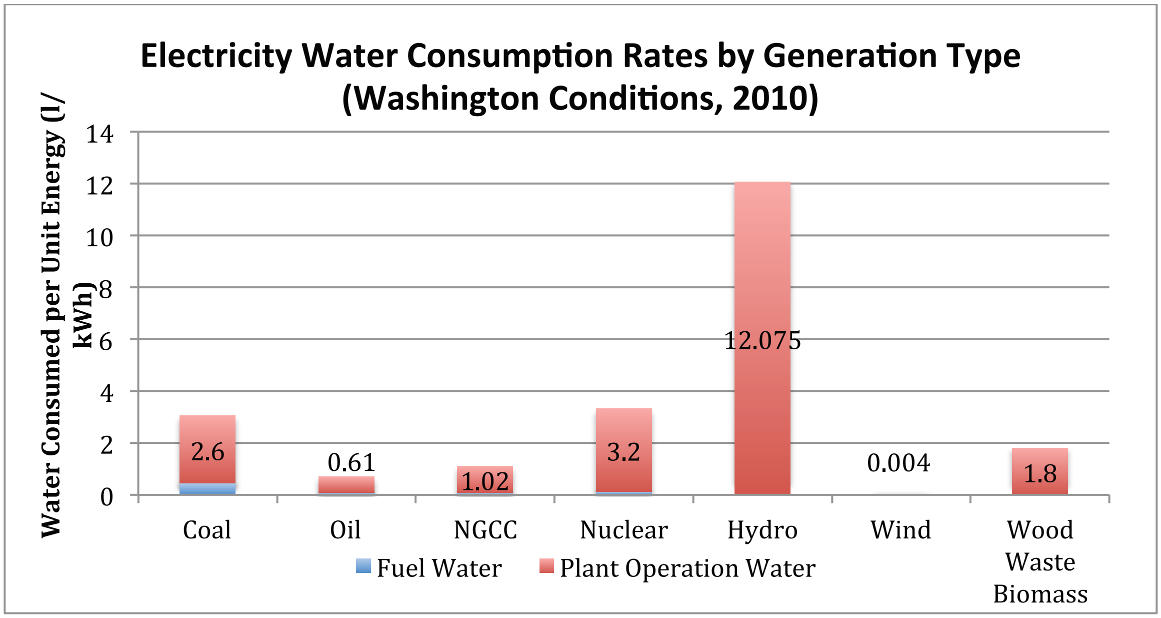


Figure 97. Electricity Generation Water Consumption Rates, Washington Conditions in 2010.

The area where Washington's electricity-related water consumption that differs greatly from that of Georgia's electricity distribution, however, is in aggregate monthly water consumption by each source. Despite the lower evaporation rate for hydroelectric reservoirs in Washington State, hydroelectricity constitutes approximately 70 percent of the state's total monthly electricity output. Ultimately, total monthly water consumption for electricity generation is almost entirely from water consumption in hydroelectric power generation at 56.4 billion liters per month, with smaller water consumption components traceable to nuclear, natural gas combined-cycle, and coal-fired power generation (**Figure 98**). As with Georgia's electricity mix, oil-fired electricity generation consumes the least amount of water with respect to thermoelectric power generation; the lowest overall water consumption component can be traced to wind power where minute amounts of water are consumed in the cleaning and maintenance of wind turbines. While thermoelectric power generation water consumption and renewable power generation water consumption in Georgia are split fairly evenly, renewable energy-related water consumption dominates the total water consumption for electricity generation in Washington despite the significantly lower water consumption rate for hydroelectric power. In total, 56.44 billion liters of water are consumed in renewable electricity generation while 6.285 billion liters of water per month are consumed in thermoelectric power generation, leading to an aggregate monthly value of 63 billion liters of water consumed.

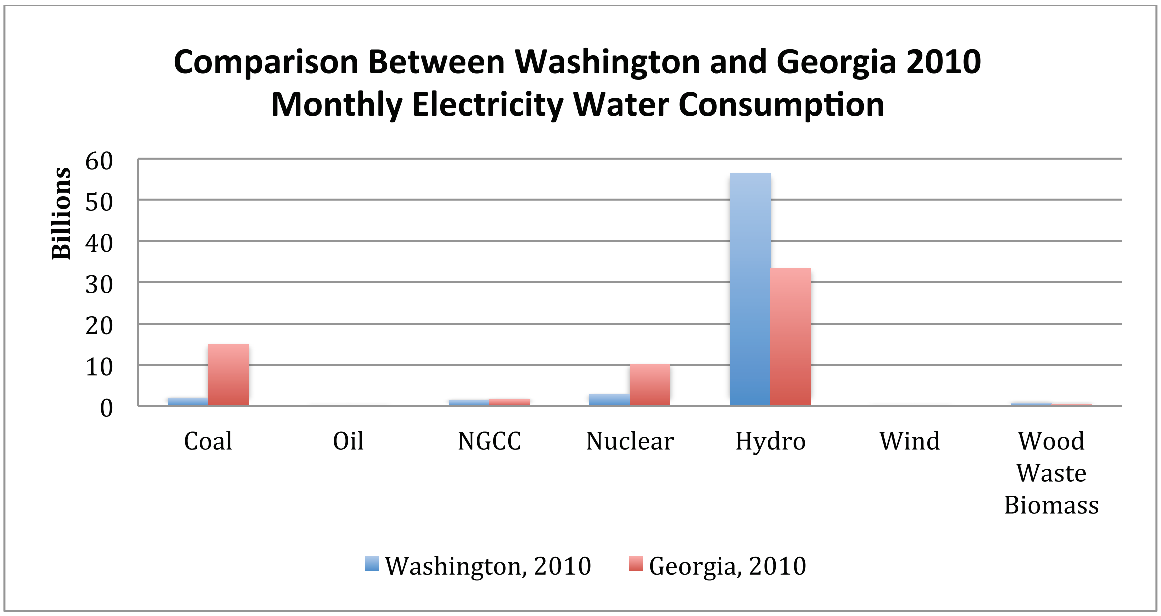


Figure 98. Comparison Between Georgia and Washington Monthly Electricity Generation, 2010 Conditions.

Table 42. Monthly Electricity Generation Water Consumption Values for Washington and Georgia 2010 Conditions.

Electricity Source	Washington Monthly Electricity Water, million l	Georgia Monthly Electricity Water, million l
Coal	1876	1499
Oil	2.8	5.6
NGCC	1264	1501
Nuclear	2729	1010
Hydro	56440	33400
Wind	0.488	0
Wood Waste Biomass	686	466

Normalizing water consumption for electricity generation based on a total monthly output of 7.757 GWh and an aggregate water consumption value of 6.3 billion liters (along with an average transmission efficiency of 0.92) yields a weighted average of **8.827 l/kWh**. This normalized water consumption value for Washington is approximately 34.2 percent greater than that of Georgia, which is somewhat lower than expected given the much greater dependence on hydroelectric power and renewable energy in Washington.

7.3.1.4. Washington Electricity Mix for 2030 Conditions

While there are modest increases in power plant generation for coal-fired sources for Washington's projected electricity mix in 2030, there are significant increases (15.5 to 19.2 percent) for nuclear and natural gas sources along with renewable energy sources which are assumed to apply to biomass, hydroelectric power, and solar power generation. The hydroelectric generation water consumption values are carried over from the 2010 electricity generation mix for Washington, while thermoelectric power plant water consumption values are carried over from the Georgia 2030 scenario.

As with Georgia's projected electricity generation in 2030, there are notable decreases in water consumption rates for thermoelectric power generation that are ultimately offset by the much greater consumption rates for hydroelectric power. This is exacerbated even further in this case in an overall context for Washington in 2030, as hydroelectric power constitutes 61 percent of the state's total monthly electricity generation profile. Ultimately, the above electricity profile results in a slightly lower normalized water consumption figure at 8.662 liters per kilowatt-hour produced compared to 8.827 l/kWh for Washington's electricity profile in 2010. This slight decrease contrasts somewhat with the more significant water consumption improvement for Georgia in 2030, where thermoelectric power generation constitutes a larger share of Georgia's electricity mix (**Figure 99**).

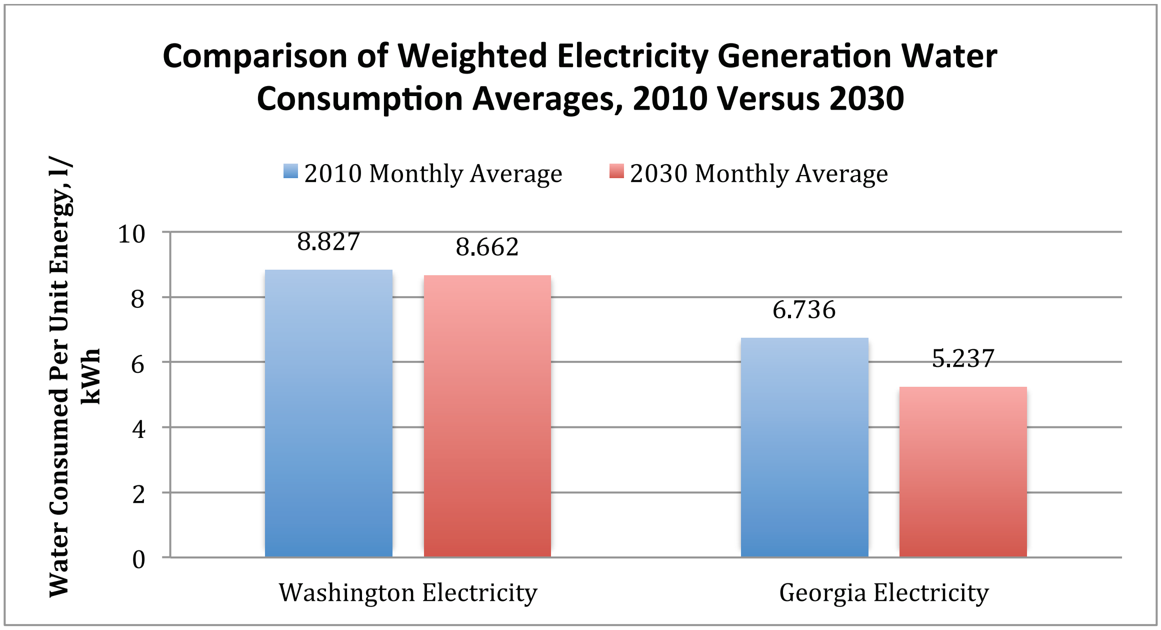


Figure 99. Comparison of Weighted Electricity Generation Water Consumption Averages for Georgia and Washington State, 2010 Versus 2030 Conditions.

7.3.1.5. Hypothetical Electricity Mix for 2030 Conditions

Applying dry-cooling plant water consumption values for thermoelectric power generation along with projected national electricity generation shares for the hypothetical case study for 2030 yields the reduced water consumption figures in **Figure 100**. With hydroelectric generation out of the mix, the most water-intensive electricity generation source is that of nuclear power plants using high-temperature gas reactors due to outlet temperatures of 1,000 degrees Celsius, although it is possible that other coolants such as helium can be used and that water is also utilized in other power plant components and functions. Otherwise, due to the implementation of dry cooling methods for natural gas and biofuel-powered plants, water consumption rates for thermoelectric power plant operation are minute to nonexistent. Furthermore, as solar and wind power plants require minimal amounts of water for washing and operation, water consumption rates for renewable energy generation are also comparatively low.

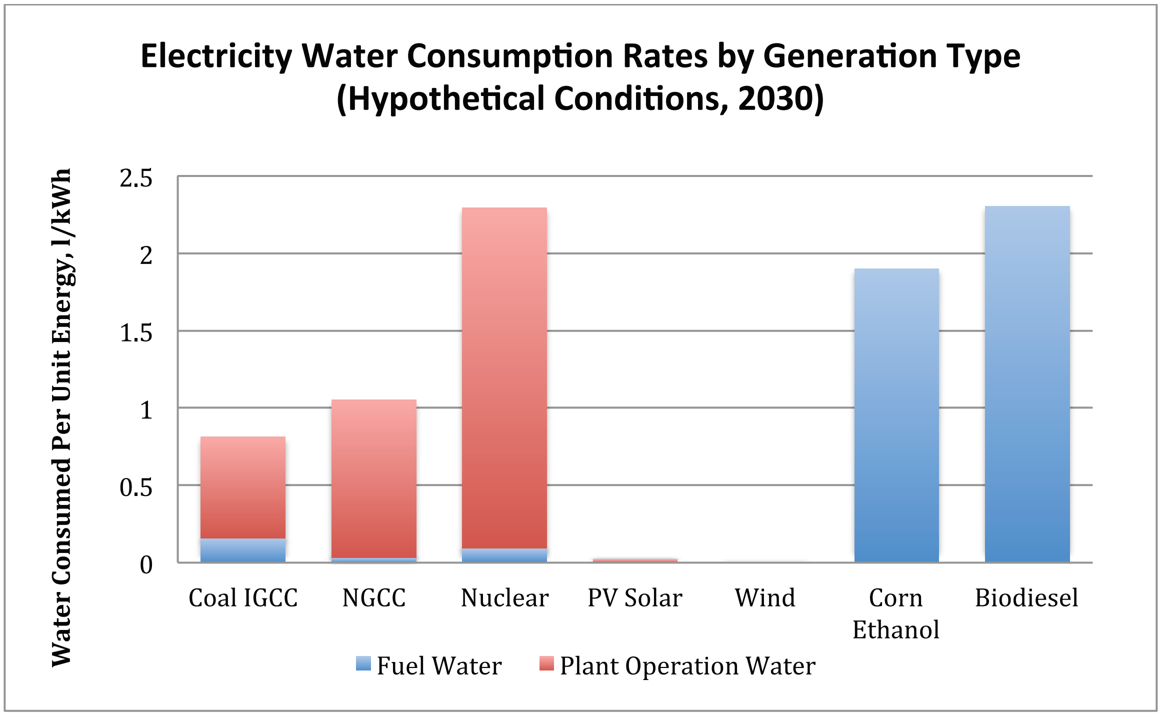


Figure 100. Electricity Generation Water Consumption Rates in 2030 Using Hypothetical Electricity Projections.

That said, the high water consumption rates from fuel production are still significant for ethanol-fired and biodiesel-fired production at 1.898 l/kWh and 2.303 l/kWh, respectively; however, the low percentage of these sources in this mix means that these water consumption factors do not influence the normalized water consumption average significantly. Ultimately, the weighted electricity generation water consumption average for plant operation and fuel production is at approximately 1 liter per kilowatt-hour, which is a significant decrease in water consumption from the Washington and Georgia electricity water consumption averages.

7.4. Automobile Fleet Water Consumption Results

The above electricity generation water consumption calculations, along with fuel production water consumption inputs, vehicle efficiency and market share parameters, and region-specific daily vehicle travel values, are applied to an automobile fleet for this case study for each scenario. Aggregate automobile fleet water consumption values based on daily driving distances, vehicle market shares, and fleet average efficiencies are summarized below in **Figure 101** and in **Table 43.**

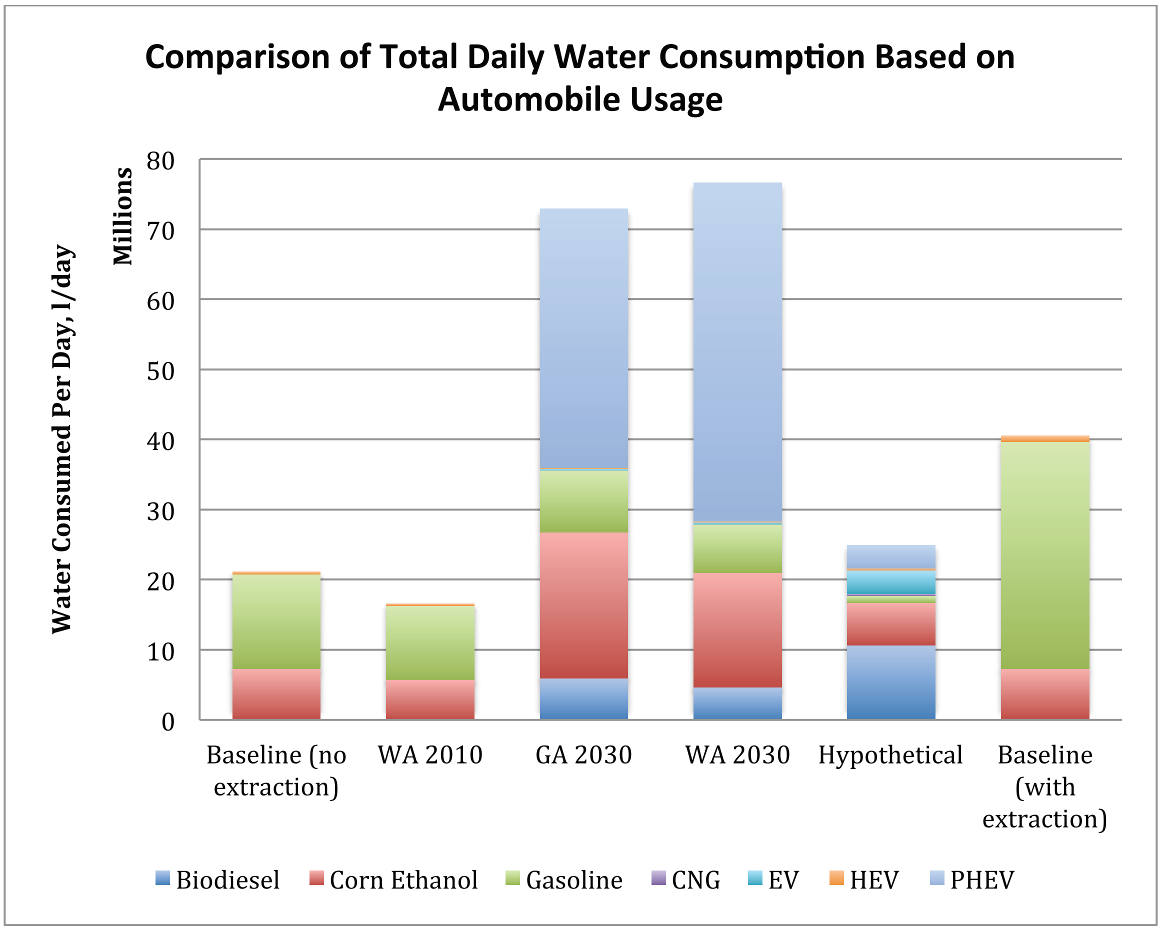


Figure 101. Comparison of Automobile Fleet Water Consumption By Scenario.

Table 43. Automobile Fleet Daily Water Consumption Results By Scenario.

	Baseline 2010	WA 2010	GA 2030	WA 2030	Hypo-thetical 2030	Baseline (with extraction)
Automobile Fleet Water Consumed, l/day						
Corn Ethanol	7,304,420	5,726,410	20,781,570	16,292,000	6,101,680	7,304,420
Gasoline	13,468,670	10,558,960	8,848,040	6936548.608	1014740	32,363,560
CNG	5,408.6	4,363.4	888.12	765.88	269,400	5,409
EV	24,090	25,325	185,340	247,480	3,312,650	24,194
HEV	330,062	258,760	192,860	151,194	323,280	792,829
Biodiesel	Not Considered		5,974,980	4,684,170	10,623,340	Not Considered
PHEV			36,925,800	48,297,510	3,250,760	

Given that the vast majority of automobiles within the transportation network using 2010 market share values are gasoline vehicles, it is fairly apparent that water consumption for gasoline vehicles represent the majority of total automobile fleet water consumption; that said, biofuel vehicles – ethanol-fueled vehicles for the 2010 case – have a significant portion of daily water consumption due to the water-intensive nature of bioenergy crop irrigation (**Figure 102**). Including fuel extraction for petroleum gasoline for the baseline scenario doubles the gasoline vehicle water consumption share.

Electricity generation plays a larger role in the 2030 scenarios with increased shares of plug-in hybrid vehicles, where the high water consumption values of electricity generation for Georgia and Washington result in PHEVs having a large share of daily automobile fleet water consumption – the reduced electricity generation water consumption value for the hypothetical scenario reduces this share of daily water consumption.

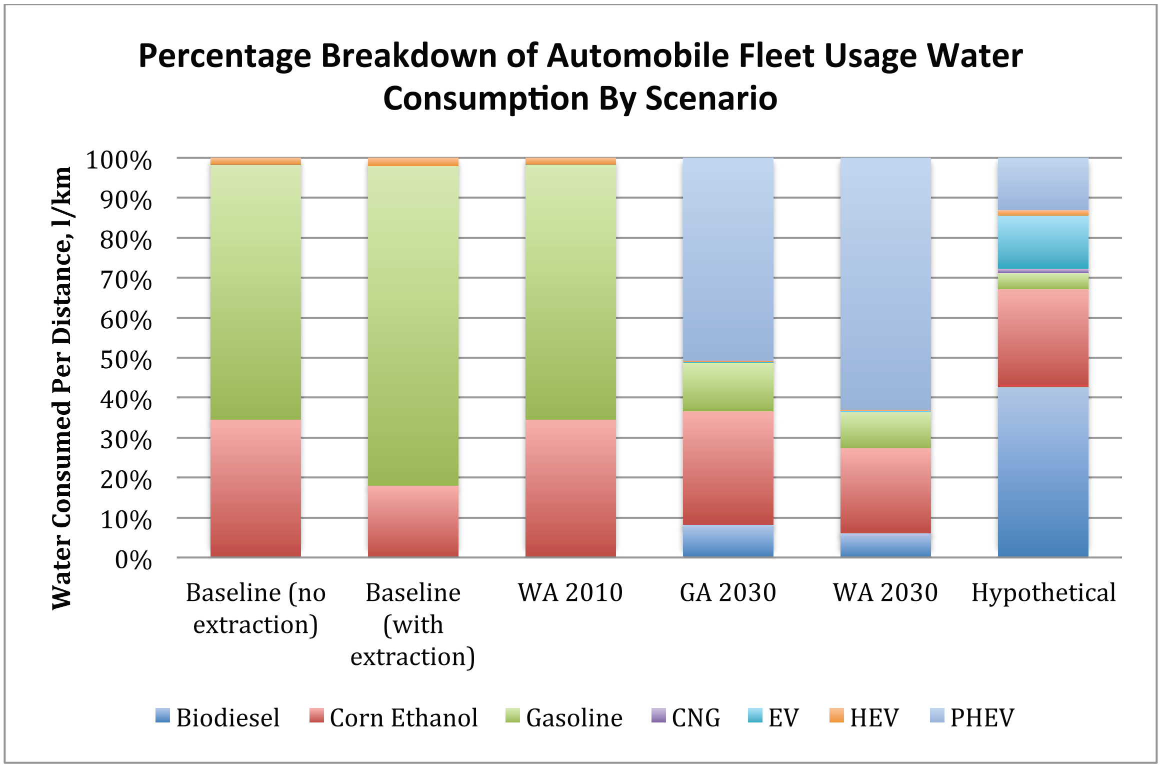


Figure 102. Percentage Breakdown of Automobile Fleet Usage Water Consumption For Each Scenario.

As with electricity generation, a normalized water consumption average can be calculated for each scenario taking into account individual vehicle water consumption rates and market share values for each vehicle type; these average values are summarized in **Table 44**. Normalized automobile usage water consumption averages for 2010 are generally the same for each state at 0.19 liters per kilometer traveled, while the introduction of plug-in hybrid vehicles and biodiesel-fueled vehicles for the 2030 scenarios yield slightly differing values between Georgia and Washington at 0.2904 and 0.2916 liters per kilometer, respectively. The low water consumption for electricity generation in the hypothetical 2030 scenario, coupled with increased shares in CNG-fueled vehicles, yields the lowest water consumption average at a value nearly half that of the other 2030 scenarios. The inclusion of fuel extraction to the baseline scenario has a similar effect as that of daily automobile water consumption in that the weighted average water consumption rate for the automobile fleet in this case study nearly doubles to 0.38 l/km.

Table 44. Automobile Fleet Usage Water Consumption Average By Scenario.

	Baseline (Georgia 2010)	Baseline (with extraction)	Washington 2010	Georgia 2030	Washington 2030	Hypothetical 2030
Average Fleet Water Consumption, l/km	0.199	0.382	0.199	0.29	0.292	0.153

The next section will detail water consumption values for each automobile transportation mode using Georgia, Washington, and hypothetical fuel and energy conditions for 2010 and 2030.

7.4.1. Automobile Fleet Water Consumption Rate Results By Vehicle Type

7.4.1.1. Vehicle Usage Water Consumption Rates For 2010 Fleet Averages

The 2010 fleet average water consumption values for the use-phase of passenger vehicles within Atlanta's mobility network can be summarized below in **Figure 103**. As previously shown in the fuel water consumption inputs for gasoline and corn ethanol, the largest amount of water consumption across all considered passenger vehicle types can be traced to electric vehicles at approximately 2.316 liters of water consumed per VKT (vehicle kilometers traveled); this high value is due to the fact that a significant amount of water is consumed for hydroelectric power generation as previously discussed for Georgia's electricity generation mix. For Washington State's electricity generation, water consumption from electric vehicle usage is significantly higher due to the state's heavy dependence on hydroelectric power generation (**Figure 104**).

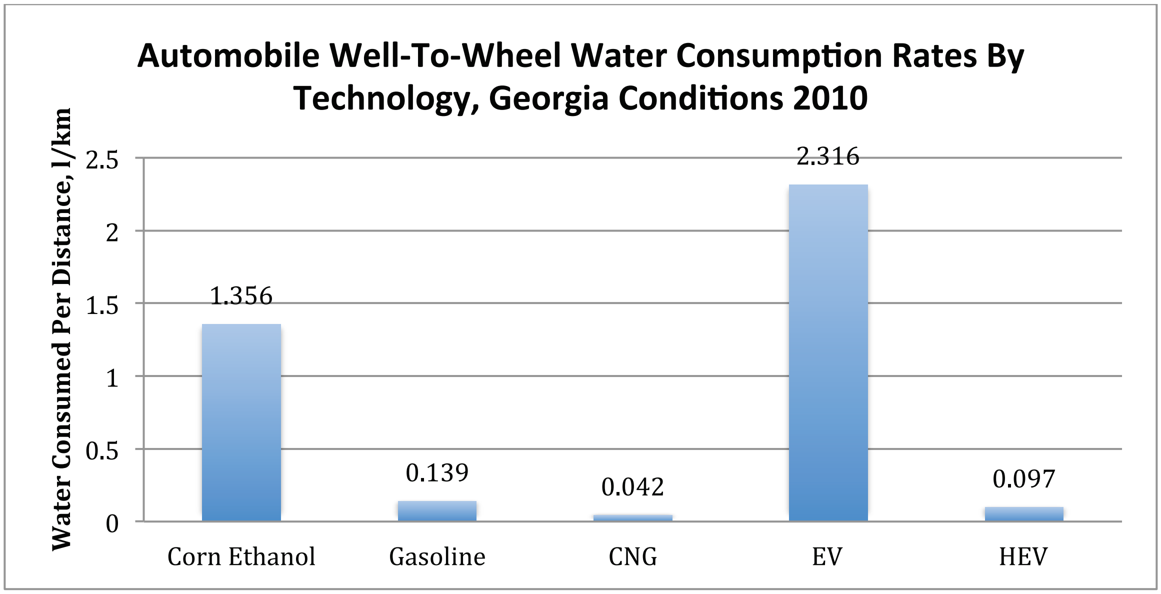


Figure 103. Automobile WTW Usage Water Consumption Rates for Case 1.

Table 45. Automobile Well-To-Wheel Water Consumption Rates for Atlanta, 2010 Conditions.

Automobile Type	Fuel Usage Water, l/km	Fluid Consumption Water, l/km	Total Usage Water, l/km
Corn Ethanol	1.353	0.003	1.356
Gasoline	0.136	0.003	0.139
CNG	0.04	0.002	0.042
EV	2.316	0.0004	2.316
HEV	0.0945	0.003	0.097

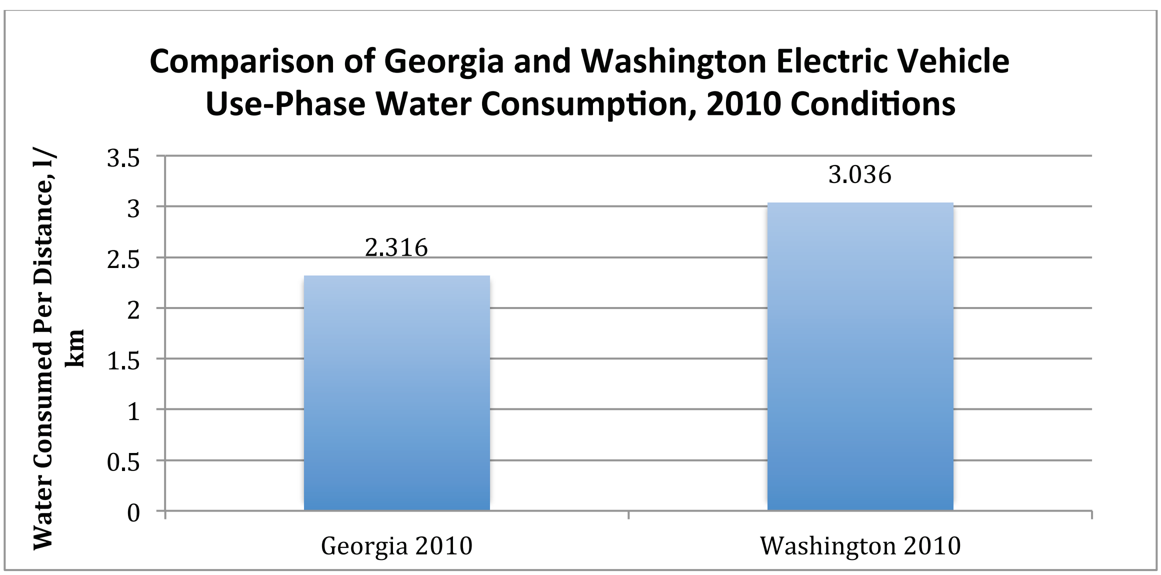


Figure 104. Comparison Between 2010 EV Usage Water Consumption Rates Between Georgia and Washington.

On the other hand, given that gasoline in Georgia is processed from imported crude oil, tank-to-wheel water consumption of local water inputs is much lower at 0.139 l/km for conventional gasoline IC vehicles and 0.097 l/km for hybrid electric vehicles. Based on in-state corn production and ethanol production, ethanol flex-fuel vehicles consume the second-highest amount of water per kilometer at 1.35 liter per kilometer; should these vehicles be using gasoline instead, the water consumption input would be comparable to that of gasoline vehicles. Even with the addition of natural gas compression via gas inputs or electricity inputs, water consumption for CNG vehicles is the lowest at 0.042 liters per kilometer, meaning that for the conditions present in Atlanta CNG vehicles would consume the least amount of water per day within this network. With all vehicle types and associated use-phase water consumption rates considered in this scenario, the weighted average water consumption per kilometer traveled for all of the assessed passenger vehicles is approximately 0.199 liters of water per kilometer – a value that is driven primarily by the large number of gasoline automobiles in this case.

It should be noted that the dominant water consumption factor in transportation mode usage is based on the amount of energy or fuel consumed in these vehicles; water consumption traced to auxiliary fluid inputs such as coolants and fluids is very little over each kilometer traveled at 0.001 l/km for each electric vehicle and up to 0.003 l/km for gasoline and ethanol vehicles.

Applying fuel extraction water consumption values for gasoline vehicles results in the significantly increased use-phase water consumption rates as shown in **Figure 105**. As noted in the overall automobile fleet water consumption comparison, this is primarily due to the water-intensive nature of oil recovery, especially for secondary extraction techniques that require water flooding or carbon dioxide injection as discussed in Chapter 3. As with natural gas water consumption for electricity generation purposes, it is assumed that water consumption for natural gas extraction is negligible.

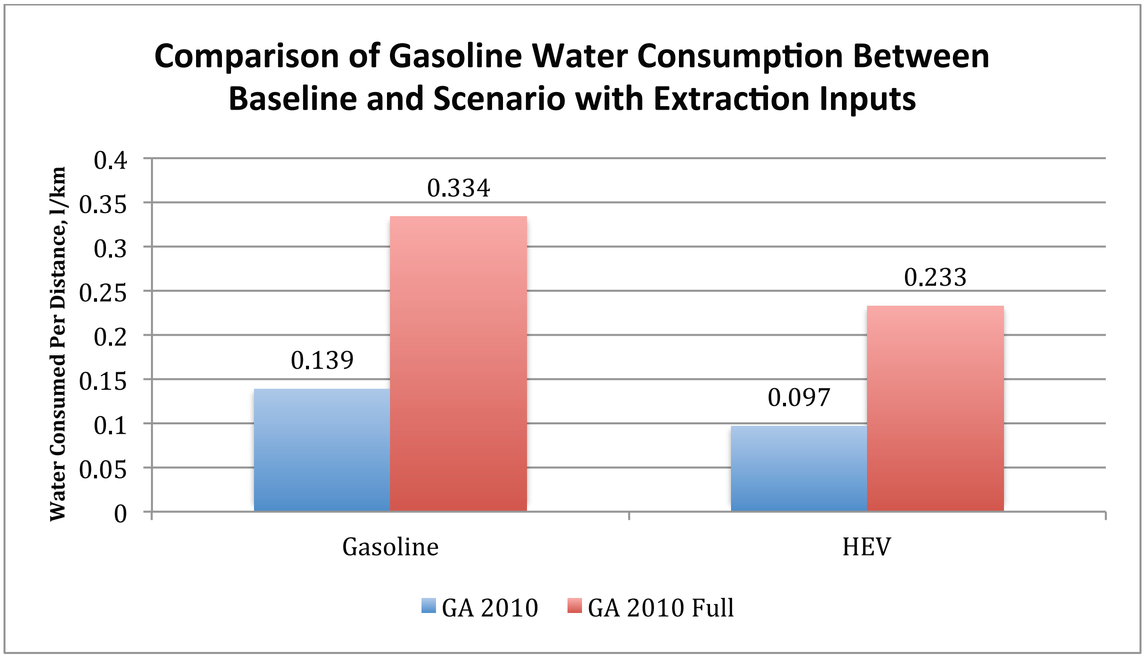


Figure 105. Gasoline Vehicle Usage Water Consumption Rates for Extraction-Included Versus Baseline Scenarios.

7.4.1.2. Vehicle Usage Water Consumption Rates For 2030 Fleet Averages

A direct comparison of per-kilometer, well-to-wheel usage water consumption for the vehicles considered in the network scenarios for 2030 (for Georgia and Washington) is summarized below in **Figure 106,** with average vehicle usage water consumption based on the above vehicle market shares estimated at 0.29 liters of water per vehicle kilometer traveled. Improved tank-to-wheel efficiency values for 2030 automobiles suggest a notable decrease in water consumption for gasoline, CNG, and ethanol-fueled vehicles.

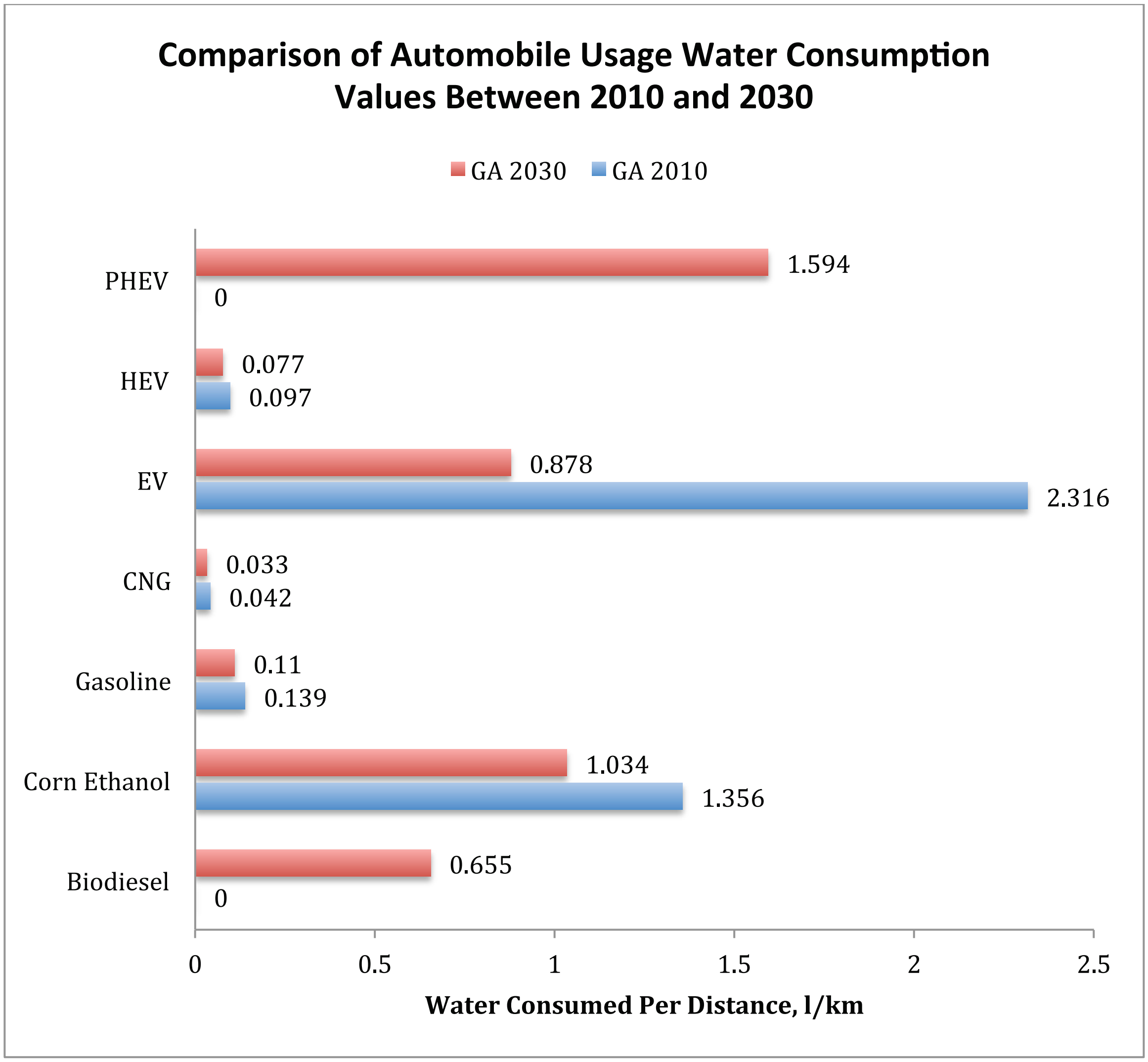


Figure 106. Comparison of Automobile Usage Water Consumption Values for 2030.

In addition to the gasoline, electric, hybrid, CNG, and ethanol vehicles that were considered in the 2010 case using Georgia's energy profile, plug-in hybrid and biodiesel-fueled vehicles are also considered, where the use-phase water consumption rate for plug-in hybrid vehicles is the highest of all the vehicles assessed at 1.544 liters per kilometer for Georgia's electricity mix and 2.6 liters per kilometer for Washington's electricity mix; that said, this is ultimately less than the highest water consumption rate in 2010 traced to electric vehicles (**Figure 107**).

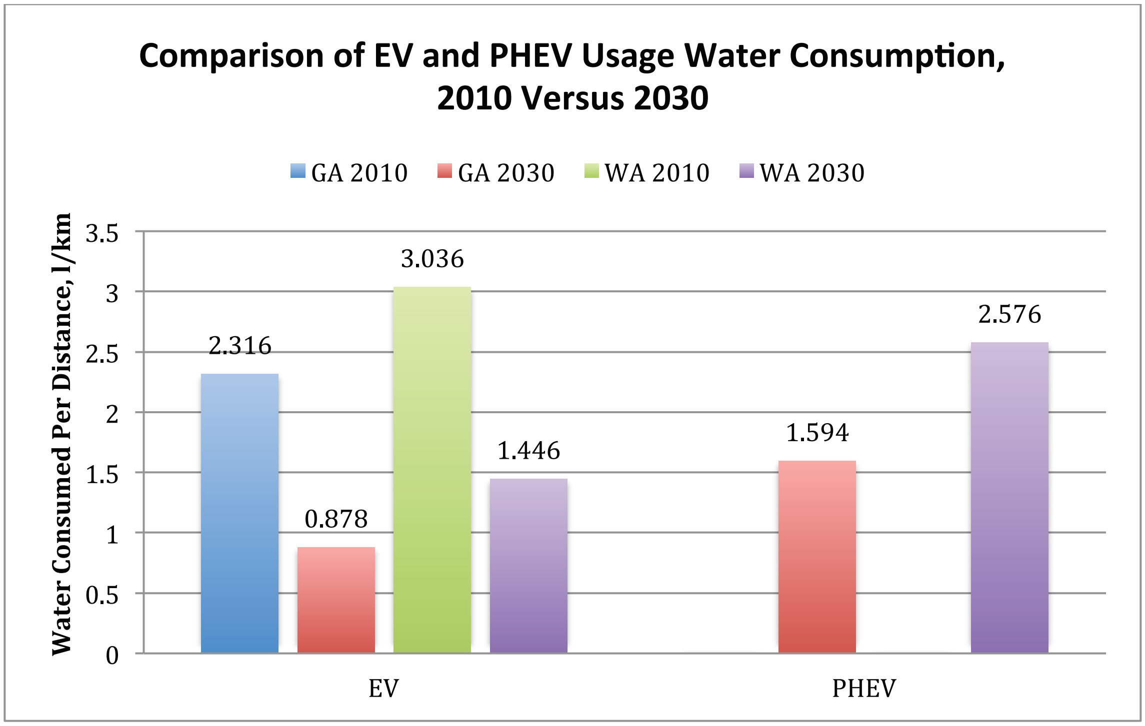


Figure 107. Comparison of Electric Vehicle and PHEV Usage for 2010 and 2030 Conditions. PHEVs were not considered for 2010 conditions.

Assuming improved energy efficiency in battery electric vehicles, use-phase water consumption for EVs in 2030 is much lower at 0.848 liters per kilometer due to the lower energy consumption value and average water consumption rate for electricity generation for 2030; for Washington's projected electricity generation water consumption, this value is significantly higher at 1.446 liters per kilometer. Biofuel-powered vehicles consume significant amounts of water traced to the production of soybean-based biodiesel and corn ethanol; these water consumption figures are at 0.655 and 1.034 liters per kilometer, respectively. Improvements in fuel efficiency for gasoline and CNG vehicles mean that these vehicle types consume the least water during their use phase for each vehicle kilometer driven. As with the baseline case, water consumption traced to the production and distribution of transportation fuels or energy sources represents the vast majority of water consumption in each vehicle type.

7.4.1.3. Automobile Usage Water Consumption Rates For Hypothetical 2030 Fleet Averages

In contrast to the above 2030 scenario results for Georgia's and Washington State's electricity profiles and fuel conditions, the hypothetical scenario results account for additional vehicle efficiency improvements as well as additional biofuel feedstock (switchgrass for ethanol and microalgae for biodiesel as discussed in Chapter 6) and a significantly altered electricity generation mix that removes hydroelectric power and includes dry cooling and emerging power plant technologies for thermoelectric and biomass sources. These variations translate to the well-to-wheel vehicle usage water consumption rates as shown below in **Figure 108**.

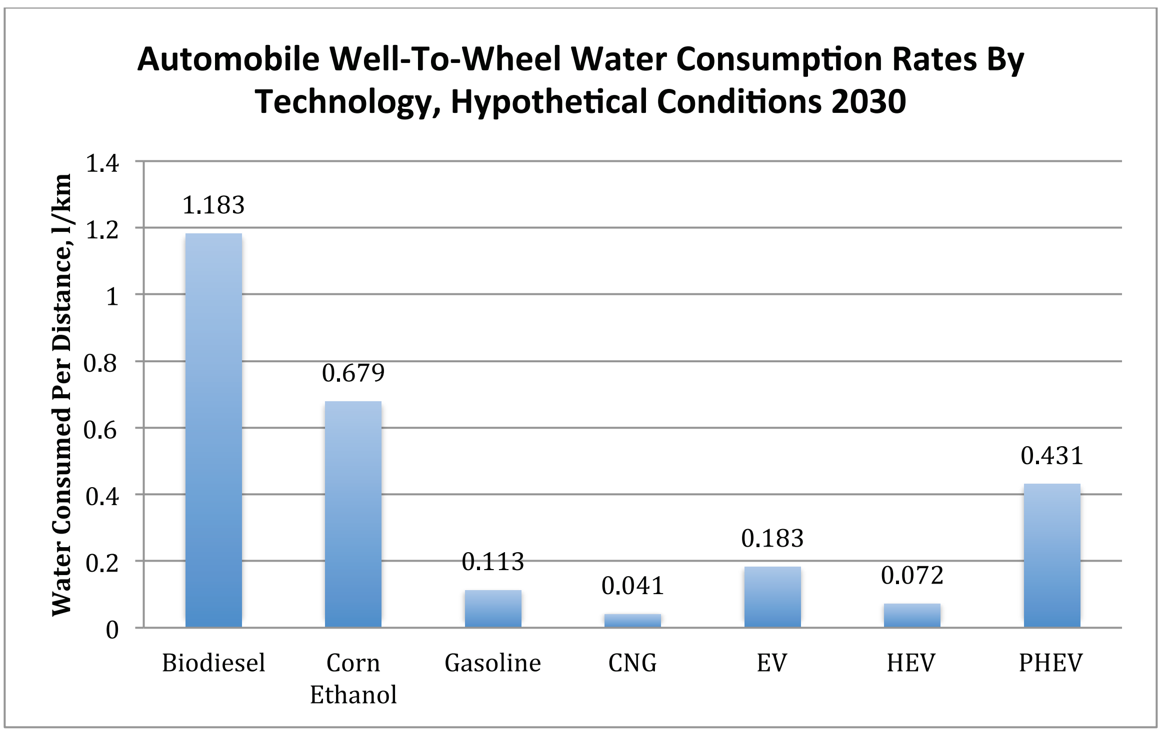


Figure 108. Well-To-Wheel Water Consumption Rates for Automobile Usage Using Hypothetical 2030 Conditions.

While there are modest fuel and energy efficiency inputs for these automobiles, the overall trend in water consumption when considering individual vehicles is very different. With the drastically reduced water consumption rate from electricity generation in this scenario, use-phase water consumption rates for plug-in hybrid electric vehicles and battery electric vehicles are much lower than those in the previous 2030-based scenarios, with the highest water consumption rates from biodiesel-powered and ethanol-fueled vehicles; in contrast to the previous results, the water consumption rates for biodiesel-powered vehicles using a 50-50 soybean and microalgae feedstock mix is higher than that of ethanol vehicles due to the higher average water consumption for fuel production from these sources; furthermore, the inclusion of switchgrass ethanol – which in this case is assumed to be from non-irrigated crops – has reduced overall water consumption from ethanol crop water requirements. Compared to previous conditions where electric vehicles and PHEVs had significantly high use-phase water consumption rates, water consumption from electric vehicle usage in this network scenario is more comparable to that of gasoline vehicles; the higher water consumption rate for PHEVs either in electric-only mode or with fuel usage is primarily due to the less-efficient electric powertrain (in this case, a higher consumption value) considered in this scenario. While overall water consumption rates for passenger vehicle usage are lower than that of other 2030 scenarios considered, the high water consumption values for biofuel vehicles are still at least six times greater than that of gasoline vehicles and almost two orders of magnitude greater than that of CNG-fueled vehicles.

7.5. Bus Fleet Water Consumption Results

Bus fleet water consumption from daily usage was also calculated in this model with the results for each set of scenarios summarized in **Figure 109** and in **Table 46.** While there is more variation in the automobile fleet between each scenario due to the reduced DVKT values for Seattle compared to that of Atlanta, this case study maintains the same DVKT value for the bus fleet in all scenarios – as with the total automobile fleet numbers in these scenarios, the number of buses were changed based on year (the hypothetical scenario has a reduced bus fleet number from that of the other 2030 cases as well as a different fleet distribution). As with the baseline and extraction-included automobile fleet water consumption results, the addition of petroleum recovery inputs nearly doubles water consumption for the diesel buses used in this fleet. As discussed in Chapter 6, diesel hybrid buses are used in place of diesel buses for the Georgia and Washington 2030 scenarios, while diesel is eschewed entirely for the biodiesel mix previously specified for the hypothetical scenario.

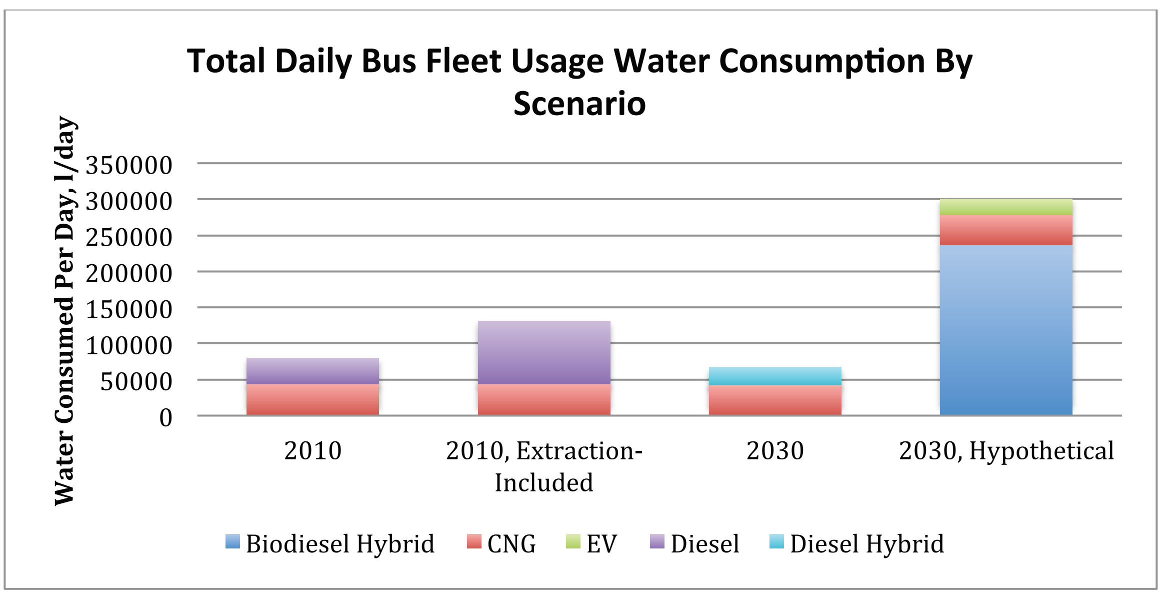


Figure 109. Comparison of Daily Usage Water Consumption For Buses in Each Scenario.

Table 46. Bus Fleet Daily Water Consumption Results By Scenario.

<table>
<tr><th>Bus Type</th><th>2010 (GA/WA) Fleet Water Consumed, l/day</th><th>2010 Extraction-Included Fleet Water Consumed, l/day</th><th>2030 (GA/WA) Fleet Water Consumed, l/day</th><th>2030 Hypothetical Fleet Water Consumed, l/day</th></tr>
<tr><td>CNG</td><td>43,885</td><td>43,885</td><td>42,749.6</td><td>40,598.3</td></tr>
<tr><td>Diesel</td><td>36,177</td><td>87,258</td><td>Not Considered</td><td rowspan="2">Not considered</td></tr>
<tr><td>Diesel Hybrid</td><td colspan="2">Not considered</td><td>24,314.1</td></tr>
<tr><td>Biodiesel Hybrid</td><td colspan="3" rowspan="2">Not considered in these scenarios</td><td>237,371.8</td></tr>
<tr><td>EV</td><td>22,344</td></tr>
</table>

It is important to note that in all of these scenarios, the majority of buses being used are fueled by compressed natural gas (approximately 73-77 percent of the total bus fleet for the first four cases and 60 percent for the hypothetical scenario). At any given time, only two or three bus types are being considered. For 2010 conditions, the baseline and Washington State scenarios show that the usage of CNG buses constitutes approximately 54 percent of overall bus fleet water consumption; these results are based on the assumption that CNG buses constitute 73 percent of the 2010 bus fleet, illustrating the water-intensive nature of diesel fuel production compared to that of CNG production and distribution. This distribution is slightly altered when considering hybrid powertrains for diesel buses, as water consumption from the usage of these buses in 2030 reduces the diesel bus share to below 40 percent.

On the other extreme, including biodiesel hybrid buses and electric buses significantly reduces daily CNG bus usage water consumption to approximately 15 percent of the overall fleet water consumption (in this scenario, 60 percent of the buses being considered are CNG-fueled). Biodiesel hybrid bus usage for a given day constitutes 75 to 80 percent of overall bus fleet usage water consumption given that 20 percent of the bus fleet constitutes biodiesel hybrid buses, while the low water consumption average for electricity generation in the hypothetical scenario means that electric buses – constituting 20 percent of the total fleet – consume less than 10 percent of total water consumption. These percentages are summarized below in **Figure 110**.

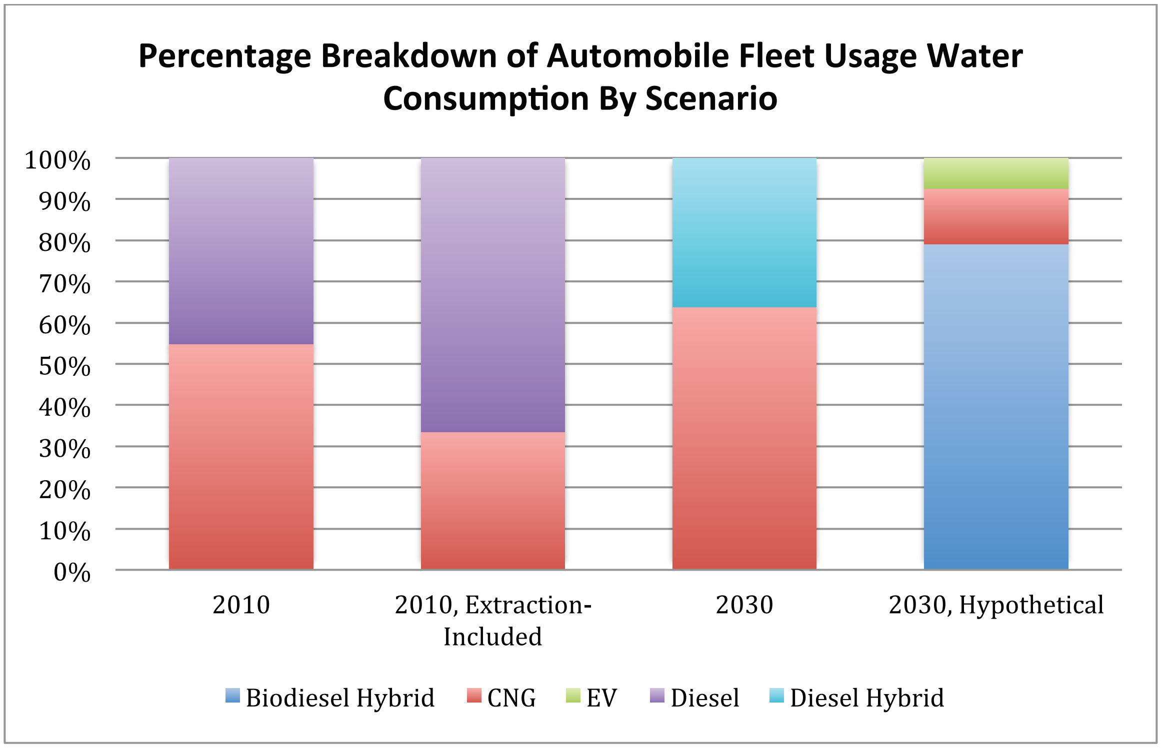


Figure 110. Percentage Breakdown of Bus Fleet Daily Water Consumption.

As with the previous set of results for the automobile fleet considered in this case study, normalized water consumption averages can be determined based on these overall results (excluding daily travel) as shown in **Table 47**. Variations in water consumption for electricity generation– a necessary component in the distribution of CNG fuel – result in minute increases in Washington scenario averages; on the other hand, the inclusion of petroleum recovery increases average fleet water consumption for Georgia from 0.55 to 0.9 liters per kilometer. Improvements in fuel efficiency and the addition of hybrid powertrains for diesel buses lowers the water consumption averages for 2030, although switching to biodiesel for these hybrid buses results in a nearly six-fold increase in average water consumption.

Table 47. Automobile Fleet Usage Water Consumption Average By Scenario.

(in l/km)	Baseline (Georgia 2010)	Baseline (with extraction)	Washing-ton 2010	Georgia 2030	Washing-ton 2030	Hypo-thetical 2030
Average Fleet Water Consumption Rate	0.548	0.8978	0.55	0.37	0.371	1.81

7.5.1. Bus Fleet Water Consumption Rate Results By Vehicle Type

7.5.1.1. Bus Usage Water Consumption Rates For 2010 Fleet Averages

Water consumption rates for the buses considered in the 2010 scenarios are summarized below in **Figure 111**. For 2010, CNG-powered buses constitute the majority of transit vehicles with the rest occupied by clean diesel buses. Based on the bus efficiency inputs for this case study for 2010 conditions, CNG-powered buses consume far less water per day during their use-phase at 0.41 liters per kilometer including fuel and fluid usage, suggesting that even with the higher fuel consumption value for CNG buses at 0.78 liters of fuel per kilometer the low water consumption in CNG production offsets this high fuel consumption value. Water consumption rates for CNG bus usage are essentially the same for Washington, albeit with slightly increased fuel production water consumption due to the increased water consumption from electricity generation. On the other hand, clean diesel buses may have somewhat lower fuel consumption but have significantly more use-phase water consumption at 0.946 liters per kilometer (**Table 48).** Based on these two bus types and associated market share, the weighted average water consumption rate is 0.58 liters per kilometer. As with passenger vehicles, the majority of use-phase water consumption in these buses is traced to the vehicles' fuel consumption per kilometer.

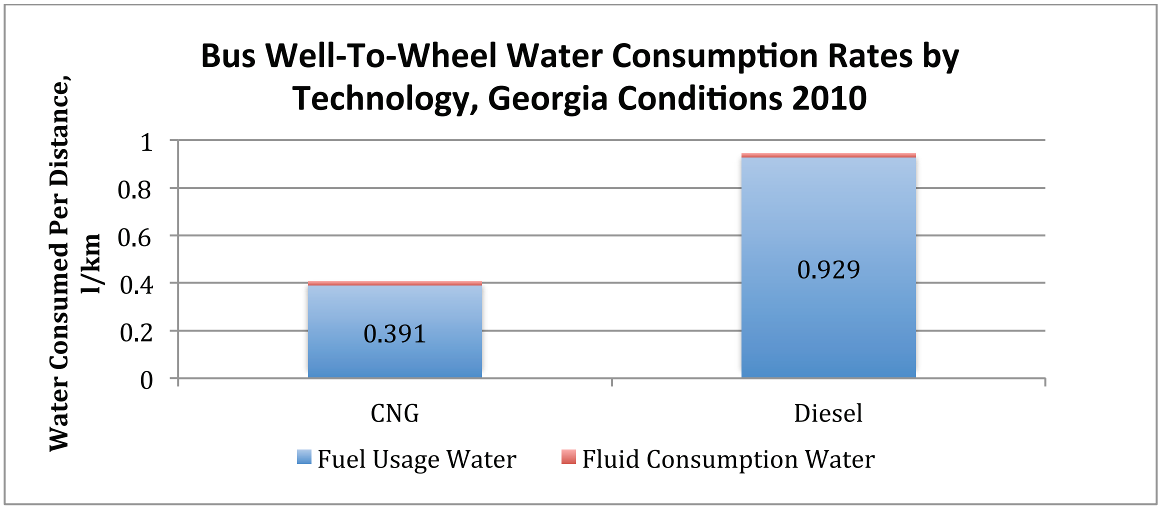


Figure 111. Well-To-Wheel Bus Usage Consumption Rates, 2010 Conditions in Atlanta.

Table 48. Bus WTW Usage Water Consumption Rates, 2010 Conditions.

Bus Type	Fuel Usage Water, l/km	Fluid Consumption Water, l/km	Total Usage Water, l/km
CNG	0.391	0.017	0.407
Washington CNG	0.393	0.017	0.41
Diesel	0.929	0.017	0.946

7.5.1.2. Bus Usage Water Consumption Rates For 2030 Fleet Averages

Water consumption rates for the buses considered in the 2030 Georgia and Washington scenarios are summarized below in **Figure 112**. For this scenario, diesel hybrid buses are used in place of conventional clean diesel buses and fuel efficiencies for both CNG and hybrid buses being considered are adjusted based on projections made by the VISION model base case. While diesel bus usage water consumption is notably greater than that of CNG-powered buses in the 2010 base case, diesel hybrid bus usage water consumption is significantly lower at 0.59 liters per kilometer due to improved vehicle efficiency. Due to the improved fuel efficiency estimate for CNG buses as well as assuming that fuel water inputs are the same as that of 2010, water consumption for CNG bus usage is also lower at approximately 0.3 liters of water per kilometer in 2030 conditions.

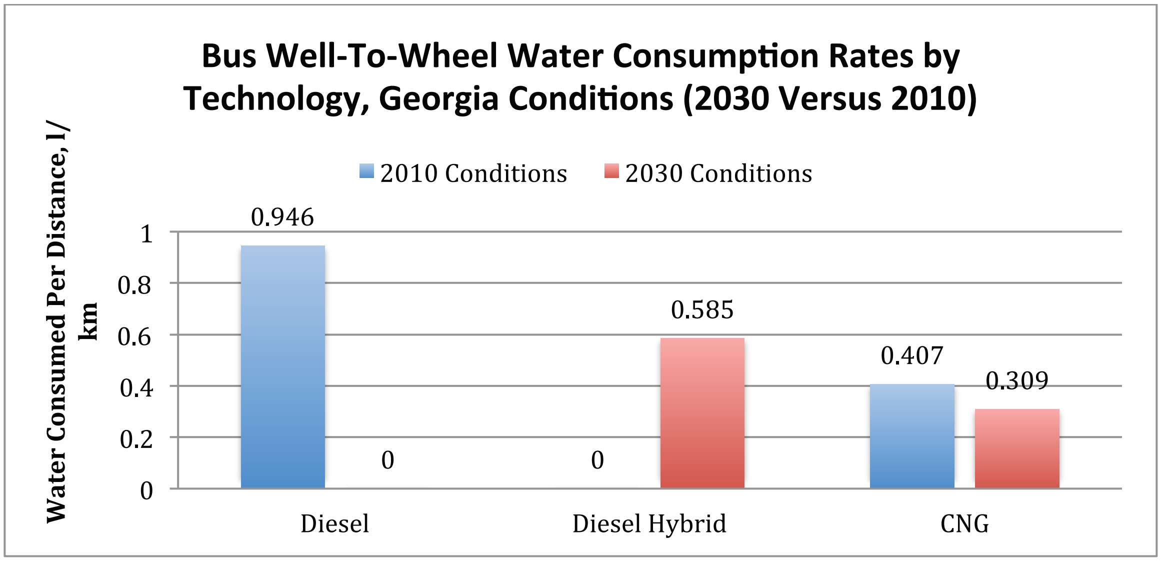


Figure 112. Comparison of Bus Well-To-Wheel Water Consumption Rates Between 2010 and 2030 Conditions.

7.5.1.3. Bus Usage Water Consumption Rates For Hypothetical 2030 Fleet Averages

Including electric buses and substituting diesel with a soybean-microalgae biodiesel fuel mix for diesel hybrid buses yields the hypothetical well-to-wheel averages using 2030 conditions shown in **Figure 113.** Even with the majority of buses being considered in this network being that of CNG-fueled buses, total bus water consumption based on this bus fleet distribution is skewed heavily towards that of biodiesel hybrid buses primarily due to that well-to-wheel water consumption values for this bus configuration is at least 70 times greater than that of CNG-fueled buses and 14 times greater than that of battery-electric buses given the previously described fuel production conditions.

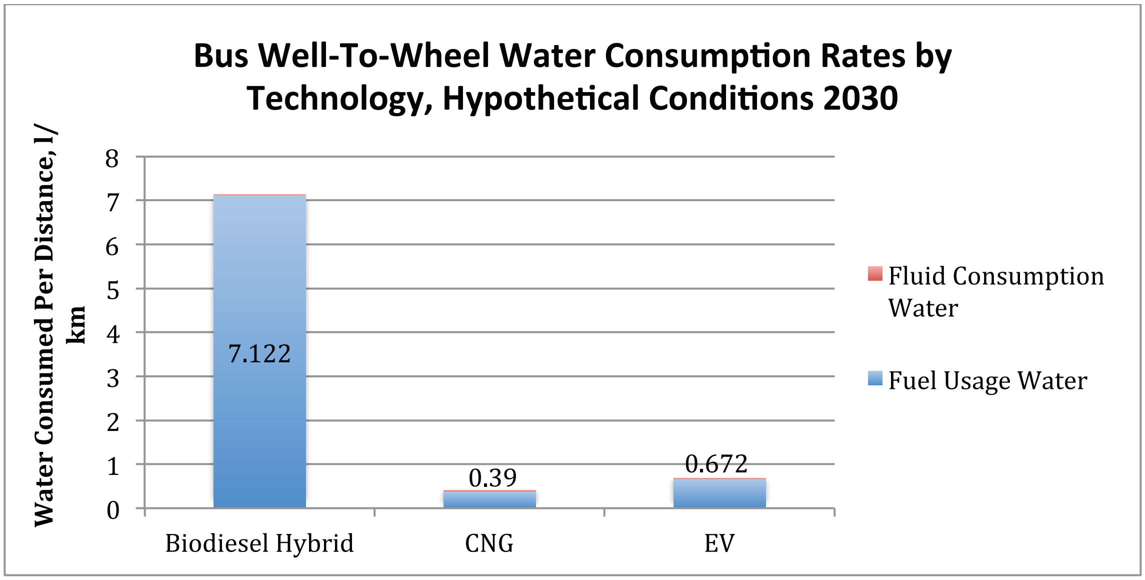


Figure 113. Well-To-Wheel Water Consumption Rates for Bus Usage Using Hypothetical 2030 Conditions.

7.6. Road Infrastructure Water Consumption Results

Compared to the large amount of water consumption for transportation mode usage, aggregate water consumption values for road operation and maintenance for both 2010 and 2030 conditions, as shown below in **Figure 114,** are very low as this model does not trace road infrastructure water consumption to individual vehicles and look instead at all of the public roads used in Atlanta based on the previously defined road length and material/energy inputs. In 2010, daily water consumption for the maintenance and operation of highways in Atlanta are the highest at 0.14 liters and 11,219.4 liters of water across 1700 lane kilometers of interstates and highways within the network. Although annual inputs per kilometer of arterial roads based on the data provided by Spielmann et al (2007) are much lower than those of highways, the large amount of arterial roads considered in this case study (at a total of 13,916 lane kilometers) means that total daily operation and maintenance water consumption is at 8745.2 and 0.129 liters, respectively. On the other hand, the relatively low amount of material and energy inputs for collector roads (streets and avenues in this case) results in lower daily water consumption values at 0.079 liters for maintenance inputs and 1496.6 liters for operational inputs. All of these road operation water consumption inputs add up to approximately 21,461 liters per day.

The decreased electricity generation water consumption for Georgia's projected electricity profile in 2030 is offset by the increased road lengths for Atlanta based on expansion plans from the Atlanta Regional Commission, meaning that ultimately daily operation water consumption for the roads in this network scenario for 2030 increases slightly to 12,140.4 liters per day for highways, 10,690 liters per day for arterial roads, and 1,562 liters per day for collector roads and streets. The majority of water consumption for road operation is traced to water consumption requirements of salt for road de-icing; it is possible that less water-intensive de-icing material inputs or no de-icing may be used for road infrastructure operation in the future.

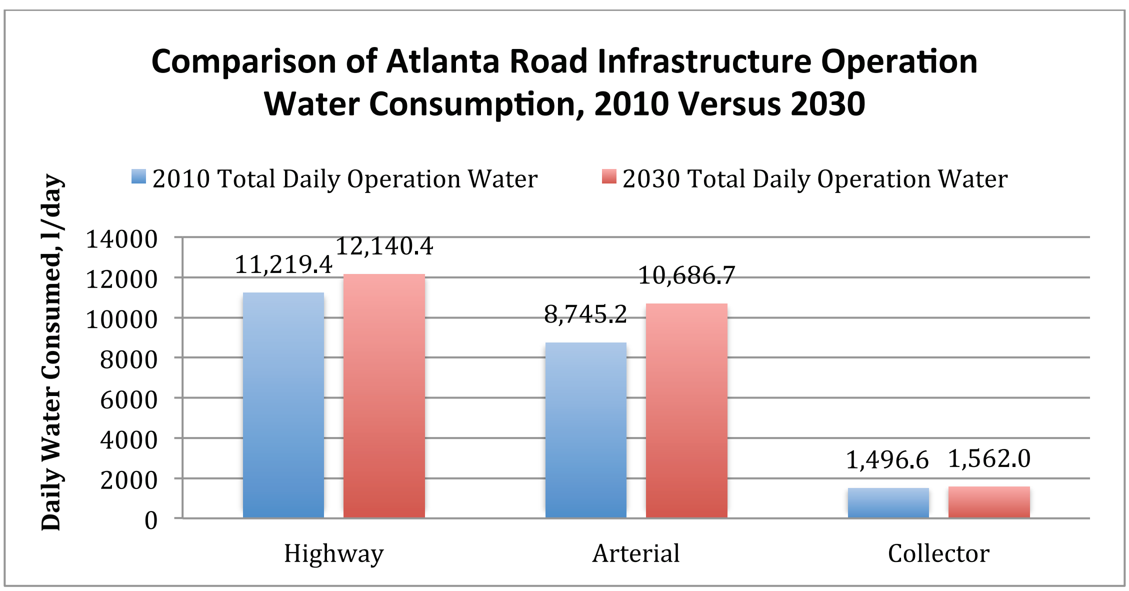


Figure 114. Comparison of 2010 and 2030 Total Daily Road Infrastructure Water Consumption Requirements.

As with the baseline case, these material and energy consumption inputs are based solely on Swiss road conditions and may not accurately reflect material and energy inputs for roads in Atlanta or in the United States. Material and fuel inputs for road maintenance are assumed to be the same for 2030 as that of 2010, while variations in overall water consumption for road operation across all of these scenarios can be traced to the network's imposed electricity generation mix. The next few sub-sections detail water consumption inputs for these material flows – assumed to be static throughout each scenario for each road lane-kilometer – along with water consumption inputs from the operation of each road's electrical components.

7.6.1. Material Consumption Inputs for Road Operation

As shown above, the vast majority of water consumption for these roads can be traced to operation material and energy inputs for each of these roads; within each of these operational inputs, almost all of the water consumed can be traced to water required to produce salt for road de-icing inputs; water inputs for the total amount of sale used for each group of roads is at least three orders of magnitude greater than that of annual water inputs for road paint or electricity requirements (**Figure 115**). The next largest group of water consumption can be traced to water consumed in producing the paint for road marking, while road lighting and signage electricity inputs represent the lowest annual water consumption rates.

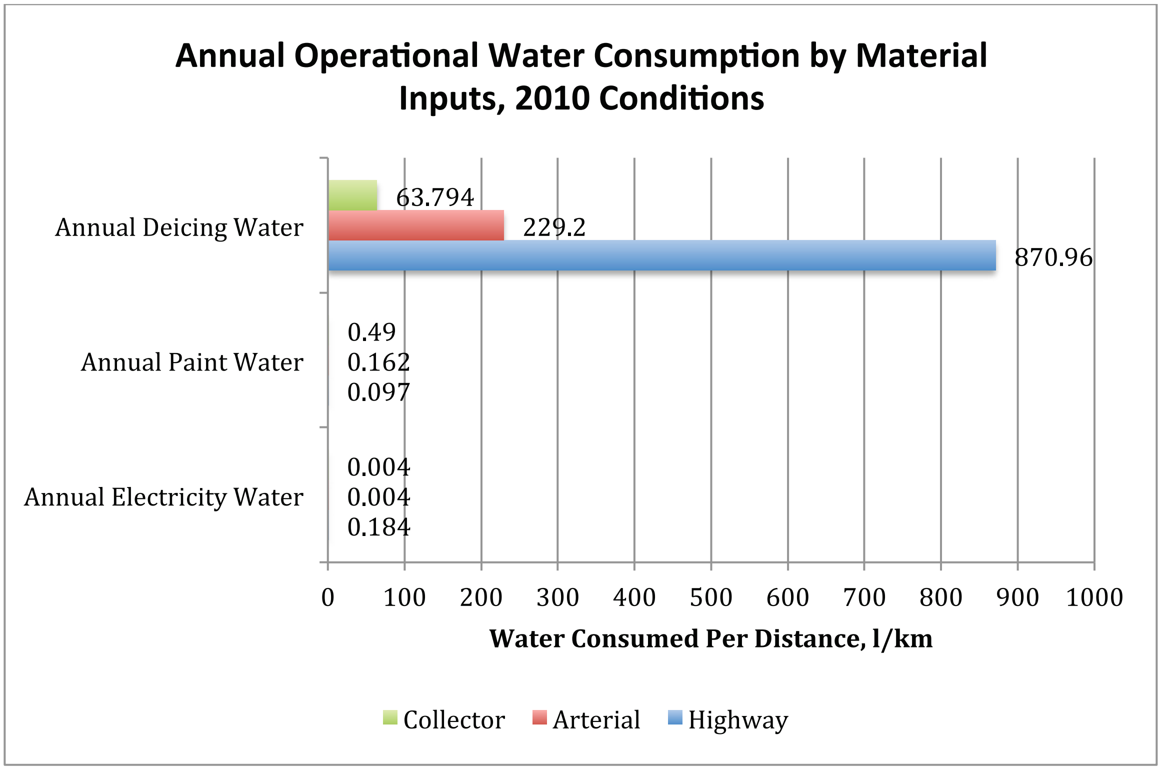


Figure 115. Annual Water Consumption Rates for Road Operation Inputs.

It is important to note that the material consumption rates for de-icing inputs are based on Swiss road conditions and are certainly not applicable to regions that do not have regular freezing or snow conditions; if this material input is removed, water consumption for daily road operation would be comparable to that of maintenance inputs. As shown in **Table 49**, water consumption for road infrastructure operation drops by two to three orders of magnitude from the baseline water consumption values. This assumption continues on to the hypothetical 2030 scenario where reducing water consumption for electricity generation propagates directly to a significant decrease – ranging from 67 to 80 percent overall – in water consumption for road electricity inputs as shown in **Figure 116**.

Table 49. Comparison of Daily Road Infrastructure Water Consumption Between Baseline/2030 Scenarios and Scenarios Without De-icing.

Road	2010 Baseline Daily Operation Water, l/day	2030 Georgia Scenario, l/day	2030 Hypothetical Scenario, l/day	2030 Georgia Scenario, No Salt
Highway	11219.382	12140.407	1.883	**3.431**
Arterial	8745.24	10686.696	7.74	**7.854**
Collector	1496.64	1562.04	11.992	**12.052**

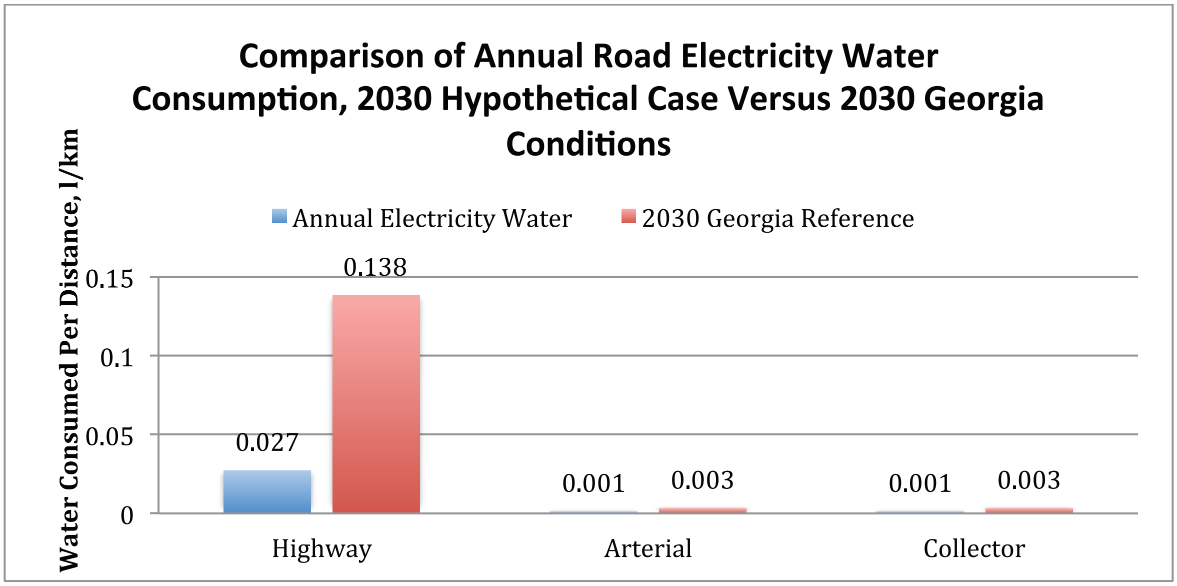


Figure 116. Direct Comparison of Annual Road Electricity Water Consumption Between Georgia 2030 Case and Current Scenario (Salt Inputs Excluded).

7.7. Sensitivity Analysis: Vehicle Infrastructure Water Consumption

Up to now, the results for this model have focused mainly on vehicle usage water consumption, any associated energy or material flow water consumption (such as in fuel production and electricity generation), and road infrastructure usage water consumption – despite the inclusion of vehicle servicing and washing as part of the structural and analytical breakdown of this system model. This is due to the observation that the validity and consistency of water consumption data for vehicle servicing and washing is somewhat questionable; instead of allocating service infrastructure usage water consumption as part of the scenario results, this section will focus on a sensitivity analysis on how including such water consumption components can affect network-wide water consumption as a whole.

7.7.1. Vehicle Servicing and Washing Infrastructure Inputs

As noted in **Section 5.2.2.4**, use-phase water consumption pertaining to vehicle service infrastructure in this transportation system can be decomposed into water consumed indirectly from electricity generation and direct water inputs for vehicle servicing or washing.

Vehicle servicing and washing values are sourced from Spielmann et al (2007) and Brown (2002) as previously noted and as shown in **Table 50.** Service energy inputs are separately available for automobiles and public transit buses. On the other hand, Brown (2002) gives no delineation between automobiles and buses is given in his assessment's car wash water usage results; for this case study, conveyor-based facility water consumption is applied to automobiles, while in-bay washing is applied to buses.

Table 50. Vehicle Service and Washing Inputs (Spielmann et al, 2007; Brown, 2002).

Vehicle Type	Vehicle Service Electricity, kWh/yr	Washing Water Consumption (Evaporative Losses), l/wash			Washing Interval, days
		In-Bay Washing	Self-Serve Washing	Conveyor Washing	
Automobiles	583	49.043	14.366	22.652	14
Buses	5426	n/a (in-bay washing assumed)			n/a

However, it is important to note that some of the values are not exclusively traced to water consumption. Brown (2002), for example, present water usage values and evaporation rates for a survey of vehicle washing facilities in Orlando, Phoenix, and Boston based on three commonly-used configurations; in order to apply the water usage data to this model based on the overall scope of water consumption, the water usage values for each set of car wash facilities was multiplied with the average evaporation rate for each type of facility (Brown, 2002). In order to condition the input parameters for this model, a time interval indicating the elapsed time between vehicle washes was included and set at 14 days; this is not necessarily indicative of normal vehicle usage and such an interval can vary wildly across regions and driving patterns, and variations on washing intervals will be explored briefly in the sensitivity analysis results.

While water consumption was directly not leveraged from Spielmann et al (2007), it is also important to note that the definition of consumption in this dataset is not necessarily the same as that of water consumption as specified in this model. For example, water consumption in this model is primarily traced to evaporative and seepage losses for use-phase material and energy flows, while the water consumption values in Spielmann et al (2007) may expand on this scope by including upstream water consumption or embedded water within the flow or product.

Even if water consumption was not leveraged from Spielmann et al (2007), another issue of the material/energy consumption inputs for vehicle infrastructure pertains to the scope in which the data was sourced. A closer look at bus servicing, for example, indicates that the energy consumption data stems from an inventory of bus service garages in Bern, Switzerland (Spielmann et al, 2007). As such, the input parameters are not necessarily in terms of a national scale as the sample size for such consumption results is too small to be applicable to a wide range of transportation networks. Similarly, the electricity consumption data for vehicle servicing is based on an LCI analysis of a Volkswagen Golf compact vehicle and is sourced from Germany and extrapolated to account for conditions across Europe; as such, the data is considered reliable within a small scope of automobiles and markets (Spielmann et al, 2007). As with the road infrastructure water consumption inputs, these inputs are not necessarily valid for transportation networks within the United States and there is no data for differing vehicle types or configurations. Also, considering that the electricity used in vehicle servicing facilities would primarily be to operate any facility equipment such as tools or service ramps or to operate lighting and any secondary components, these input values seem somewhat high.

As with vehicle washing, the vehicle servicing inputs were initially based on annual consumption and were amortized equally into daily consumption values. This is mainly to condition the data for this model but is not necessarily accurate. For a given automobile or bus, servicing is based on operation intervals such that these vehicles only undergo any maintenance a few times a year. In reality, vehicle servicing energy or water consumption would be characterized by a few spikes in electricity consumption for a given year within a region or transportation network. It is also important to note that not all service facilities are in peak operation for a given day as not every vehicle undergoes maintenance every day; as such, any daily consumption values may be grossly inflated.

7.7.2. Vehicle Infrastructure Water Consumption Results and Variations

Water consumption values for maintenance and washing inputs for each vehicle for the baseline case are summarized below in **Figure 117**, where the majority of daily water consumption can be traced to the water consumed in generating electricity inputs for service facilities. Based on a 14-day time interval between vehicle washes, 3.32 liters of water are used per day for each automobile and 19.5 liters for each bus. Assuming that all of the water used in car wash facilities and operations are output as wastewater or runoff, there would essentially be no water consumed in vehicle washing. On the other hand, the high normalized water consumption for Georgia's electricity generation mix (6.736 l/kWh for this case) means that 10.1 liters of water are consumed per day in service facilities for each automobile and 100.1 liters of water for each bus. If all of the passenger vehicles and buses have the same amount of maintenance inputs per day, 29.4 million liters of water are consumed per day for all automobile maintenance inputs and 63,730 liters of water for bus maintenance inputs. These aggregate maintenance inputs are near or greater than those of aggregate water consumption values for vehicle usage (**Figure 118**); however, this is assuming that all vehicles within each transportation mode in this network have the same inputs and that these inputs are *separate*, meaning that these are normalized from total electricity and water consumption for each service facility in this case study.

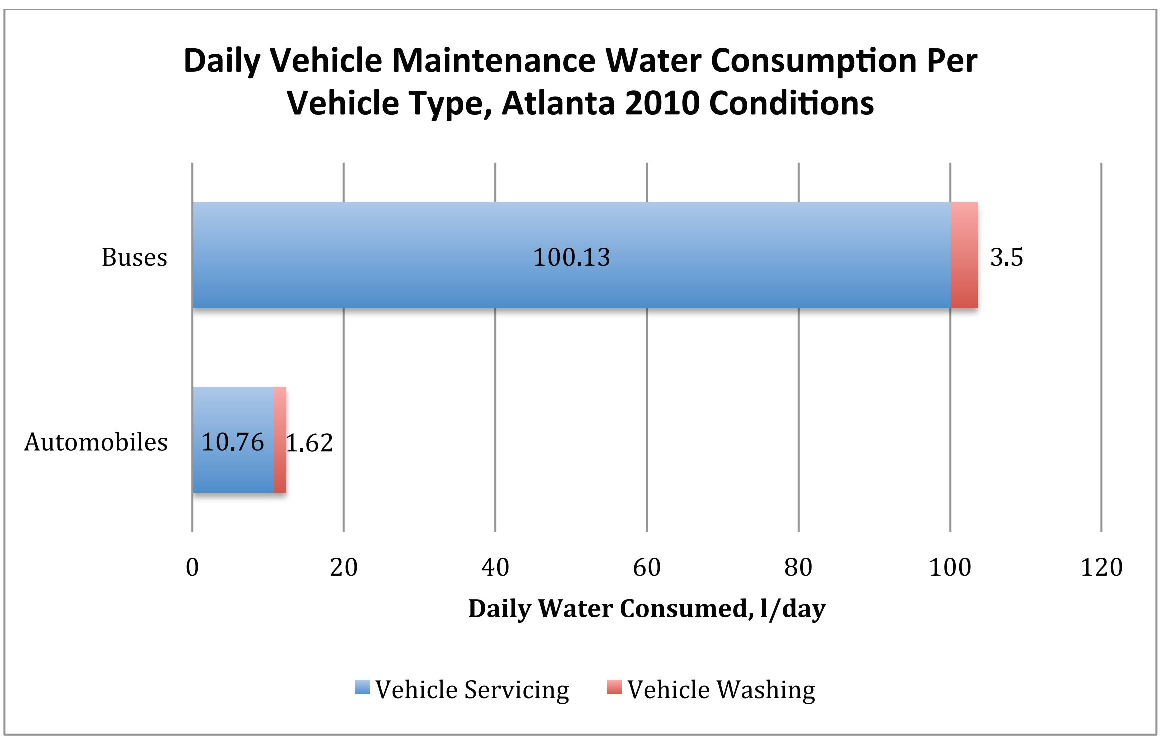


Figure 117. Daily Vehicle Mode Maintenance and Washing Water Consumption (Per Vehicle), Atlanta 2010 Conditions.

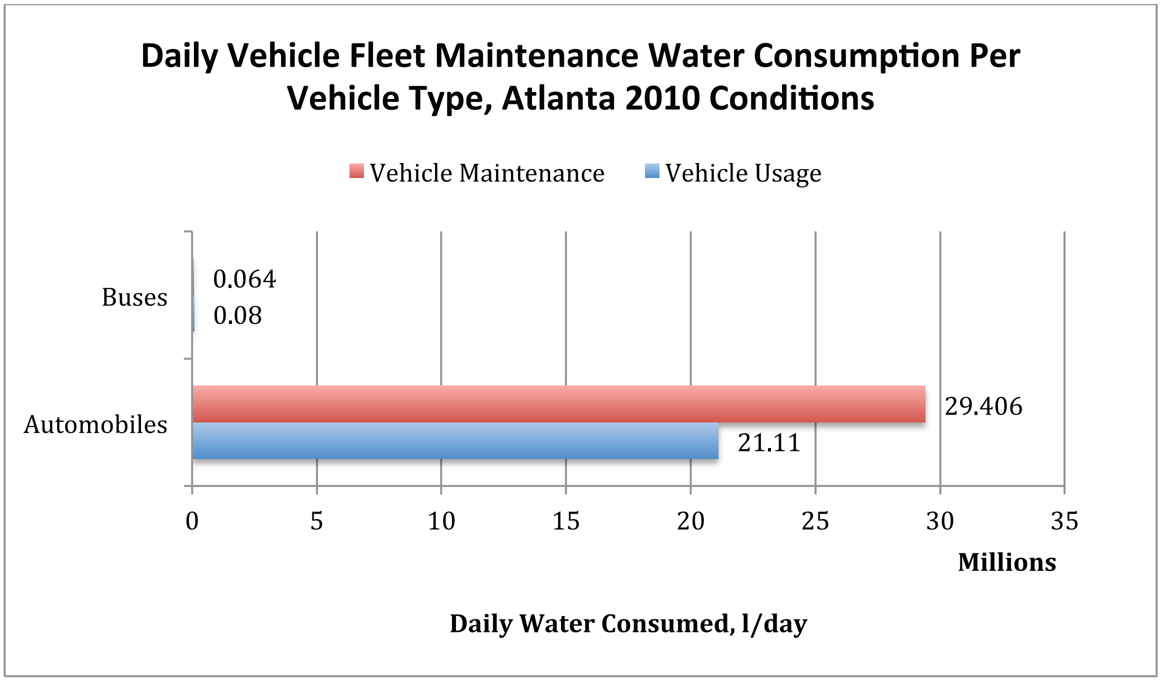


Figure 118. Comparison of Vehicle Fleet Usage and Vehicle Fleet Maintenance Water Consumption, Atlanta 2010 Conditions.

7.7.2.1. Variations in Vehicle Servicing Water Consumption

As with water consumption from electric vehicle and plug-in hybrid vehicle usage across the six scenarios in this study, water consumption from vehicle servicing inputs primarily stems from water consumed in electricity generation from the network's electric grid. This is especially apparent in the hypothetical scenario for this study where water consumption from electricity mix is comparatively low; as such, water consumption from energy flows required for servicing drops significantly in the hypothetical scenario (compared to Georgia's electricity mix in 2030, in this instance) as shown in **Figure 119.** Similar decreases in water consumption can be found when comparing against all of the other scenarios.

Ultimately, top-level total daily water consumption for vehicle infrastructure supporting the automobiles and bus fleet in this mobility network is significantly lower from the 2030 scenario with Georgia's projected electricity distribution at 7.2 million liters per day – a stark contrast to the 32.4 million liters per day consumed for the same vehicle service infrastructure for this network, albeit with far fewer vehicles being assessed compared to the 2030 case with Georgia's projected vehicle distribution and electricity profile.

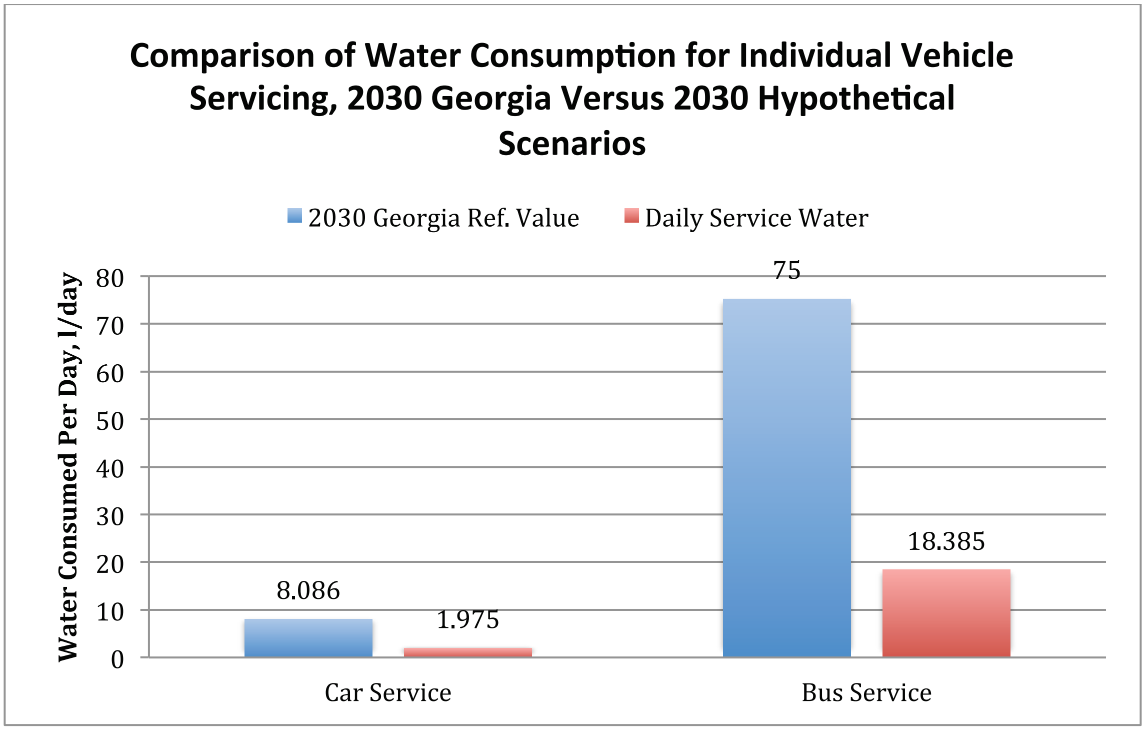


Figure 119. Direct Comparison for Vehicle Servicing Water Consumption Between Georgia 2030 and Hypothetical Scenarios.

Similar decreases in water consumption can be observed by reducing the amount of electricity used for vehicle servicing for each scenario. Reducing the annual electricity consumption to 10 percent of that specified in Spielmann et al (2007) results in an expected 90 percent decrease in water consumption for individual vehicle servicing using Georgia's electricity mix in 2010 as shown in **Figure 120**. On a network level outlook, this reduction results in a significant decrease – albeit not at 90 percent – in vehicle servicing & washing water consumption as shown in **Figure 121**.

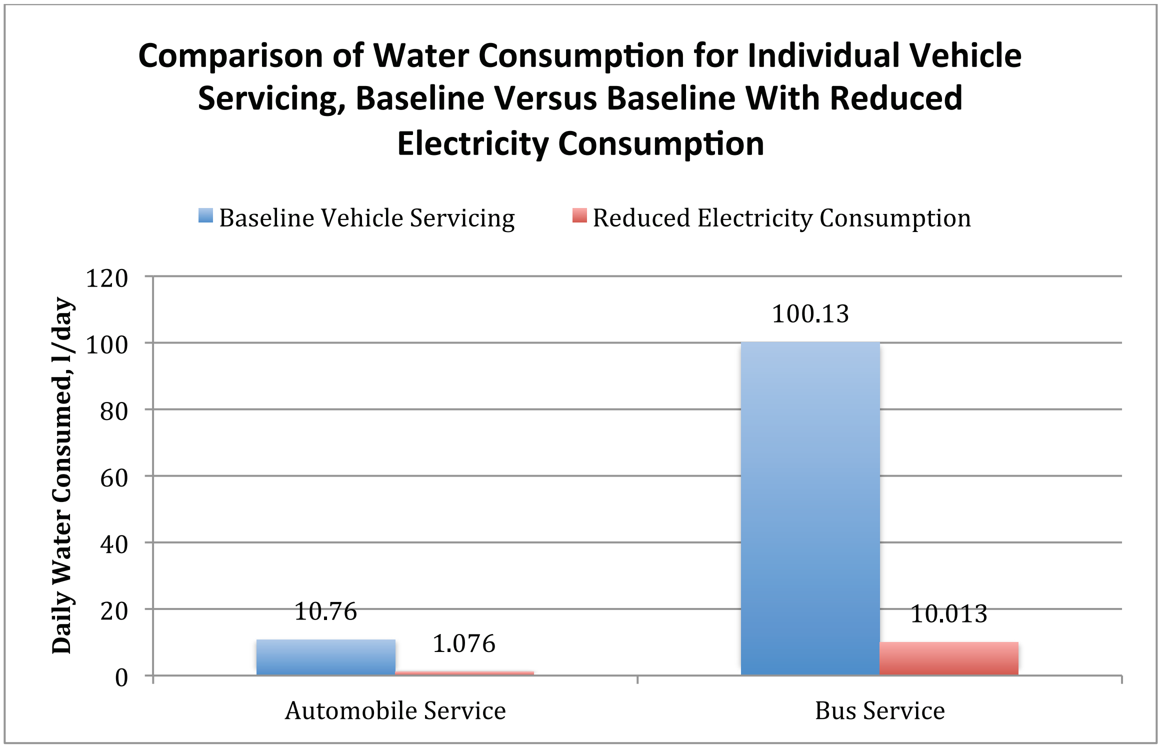


Figure 120. Direct Comparison for Vehicle Servicing Water Consumption Between Baseline and Reduced Electricity Consumption Cases.

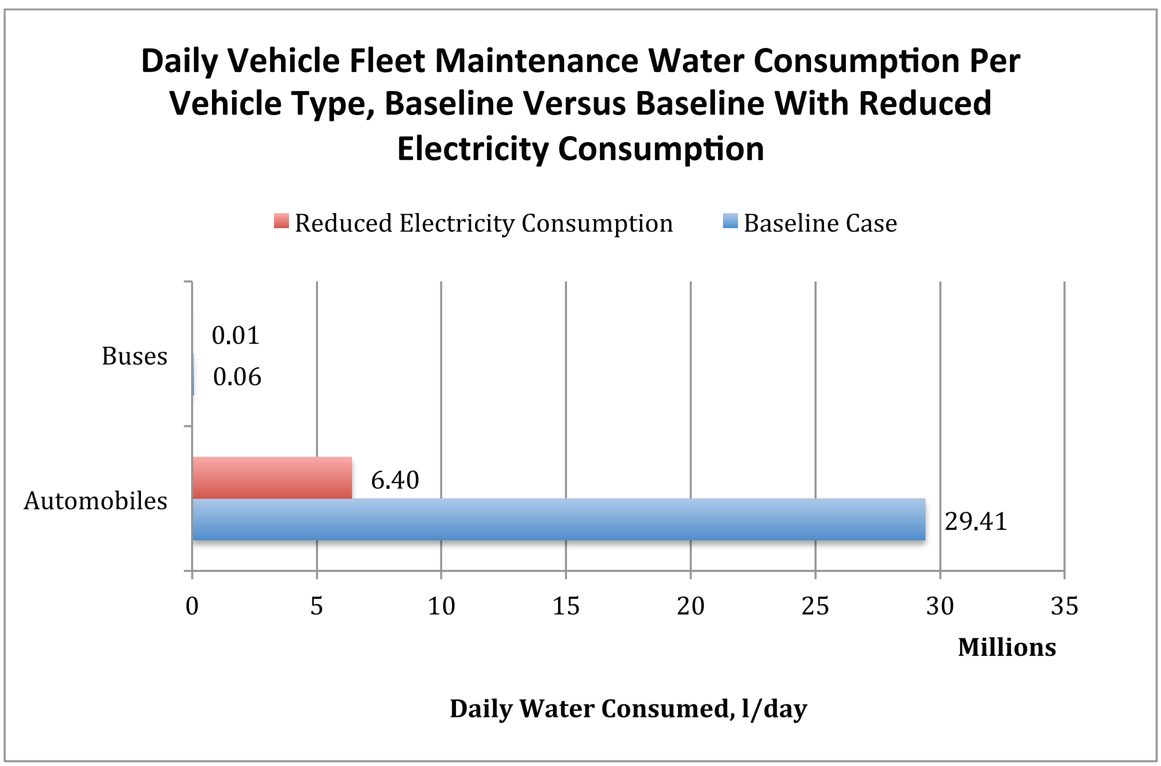


Figure 121. Vehicle Fleet Maintenance Comparison Between Baseline and Reduced Electricity Cases.

Table 51. Comparison of Daily Vehicle Fleet Maintenance Water Consumption Between Baseline and Reduced Electricity Consumption Conditions.

	Daily Maintenance Water Consumed, Baseline Case (l/day)	Daily Maintenance Water Consumed, Reduced Electricity Case (l/day)	Percentage Decrease (%)
Automobiles	29,406,015	6,399,420	78.2
Buses	63,730	8,312.4	86.9

The lower fleet maintenance water consumption percentage compared to the percentage decrease on an individual vehicle level shows that vehicle washing still plays a sizable role in vehicle maintenance water consumption. The next set of variations will focus on altering water consumption rates and washing intervals for automobile and bus washing for the baseline 2010 case.

7.7.2.2. Variations in Vehicle Servicing Water Consumption

As discussed in the input parameters for vehicle washing water usage, the vehicle washing results are based on a straight-line conversion to daily water usage based on a specified time interval between washes – in this case study, the default input value was 14 days. Furthermore, the average water usage value for vehicle washing is primarily for in-bay and conveyor-based car wash facilities – while self-serve washing facilities (and to some degree, home-based vehicle washing) use and consume less water overall. As previously noted, these values are not representative of every single region in the United States, and water consumption and washing intervals can vary wildly across transportation networks. This variability was considered in developing this model, and input parameters can easily be altered to consider different conditions.

Doubling the vehicle-washing interval to 28 days yields the altered vehicle washing water consumption results as shown below in **Figure 122**. As expected, use-phase vehicle washing consumption for each automobile and bus decreases by half, although this difference is muted when considering fleet-level vehicle infrastructure water consumption as the majority of water consumption stems from vehicle servicing inputs. Similarly, switching from conveyor-based vehicle washing to self-serve car washing yields a threefold decrease in individual water consumption based on the default washing interval; combining these results with the doubled washing interval yields the altered vehicle washing results on an individual level and on a fleet level as shown in **Table 52**. That said, any significant changes in vehicle washing water consumption are offset by any water consumption from vehicle servicing as shown on a network level.

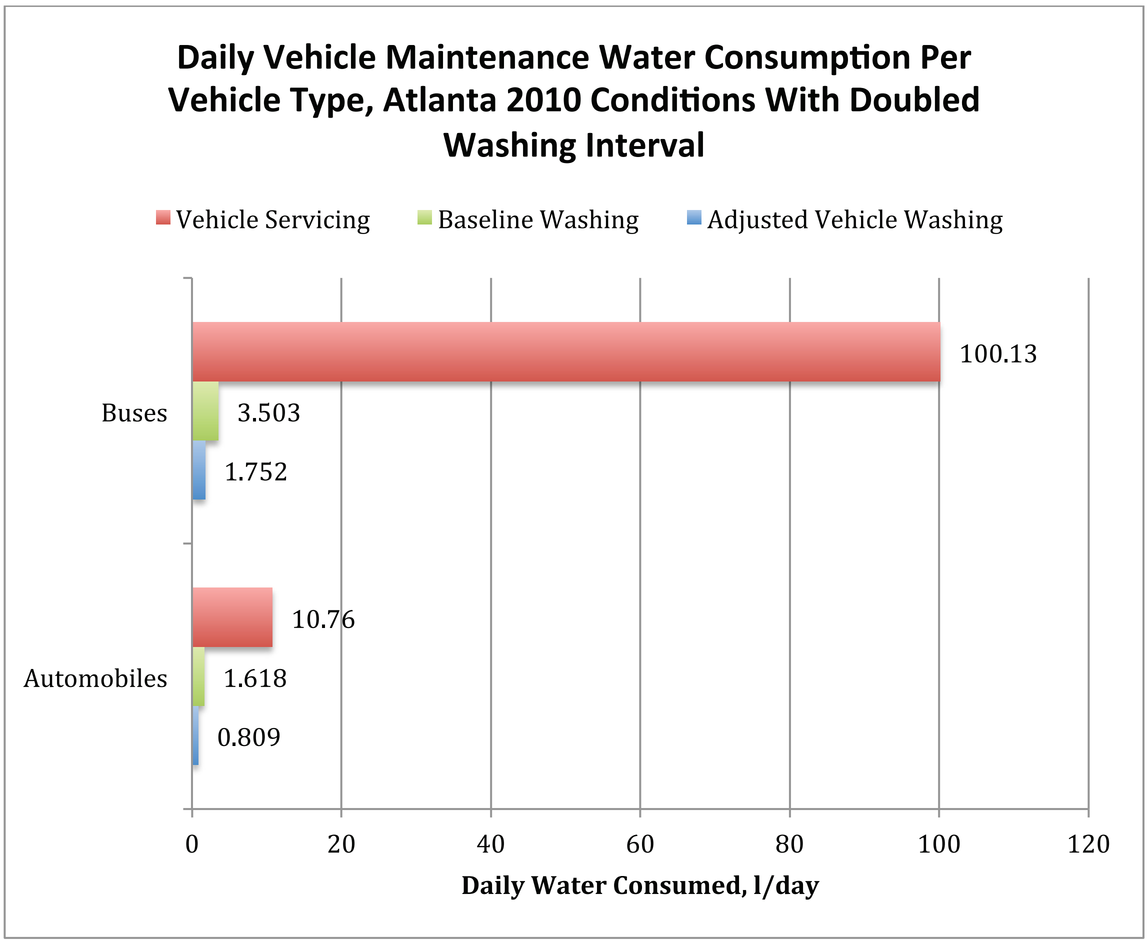


Figure 122. Daily Vehicle Mode Maintenance and Washing Water Consumption With Doubled Washing Interval, Atlanta Conditions.

Table 52. Summary of Vehicle Washing Variations In Inputs.

	Daily Washing Water Consumed, l/day	Daily Service Water Consumed, l/day	Total Fleet Infrastructure Water Consumed	Total Infrastructure Water
Default Vehicle Washing and Servicing Results				
Automobiles	1.618	10.76	29,406,015	29,466,470
Buses	3.503	100.13	63,730	
Doubled Washing Interval				
Automobiles	0.809	10.76	27,484,110	27,546,770
Buses	1.752	100.13	62,660	
Self-Service Automobile Washing With Default Washing Interval				
Automobiles	1.026	10.76	27,999,920	28,063,650
Buses	3.503	100.13	63,730	
Self-Service Automobile Washing With Doubled Washing Interval				
Automobiles	0.513	10.76	26,781,060	26,843,720
Buses	1.752	100.13	62,660	

7.7.3. Impacts on Daily Network Water Consumption

The inclusion of vehicle servicing and washing water consumption across all automobiles and buses in the Atlanta case study yields the adjusted network-level water consumption results as shown in **Figure 123**. While the validity and applicability of the above servicing inputs and results may be questionable, adding these water consumption inputs drastically increases water consumption across all scenarios by up to 3 times that of the original results. This is based on multiplying individual vehicle servicing results with the respective fleet numbers, with the baseline and Washington State 2010 scenarios registering the greatest increases in water consumption as shown below in **Table 53**. While percentage increases vary wildly across each scenario, the numerical increase in water consumption is very similar across each year and set of network conditions.

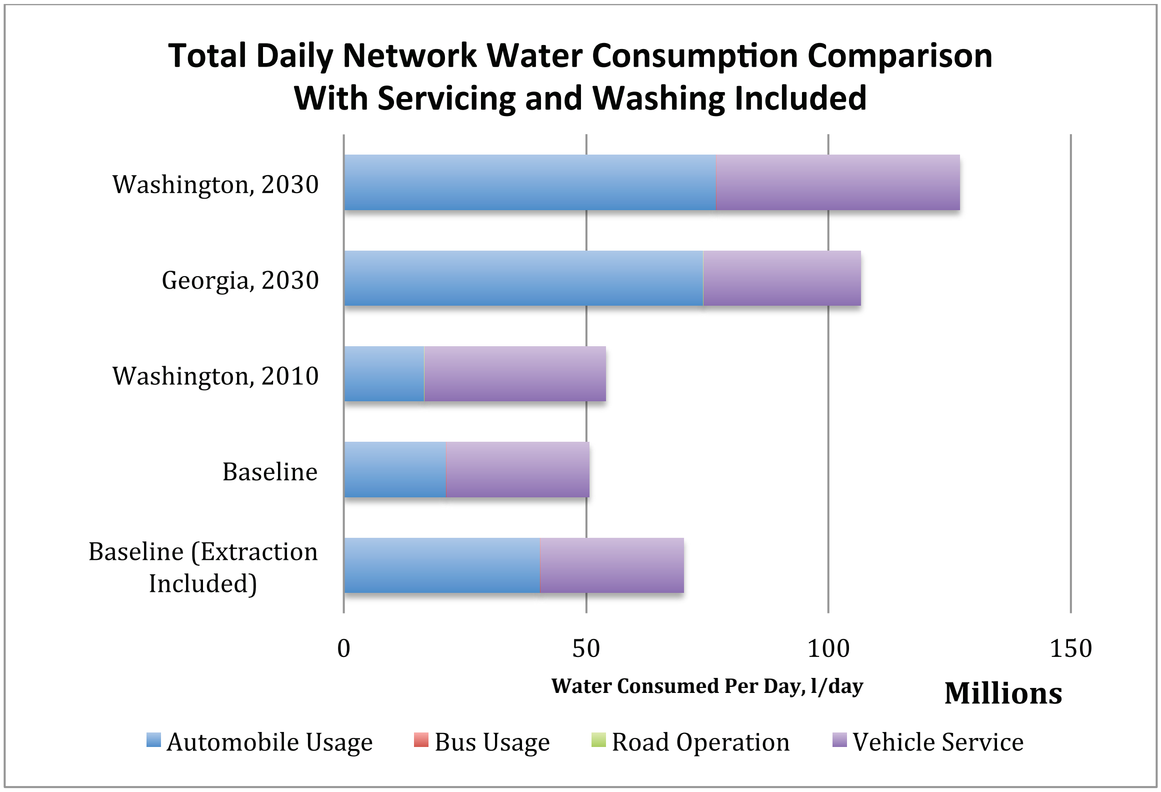


Figure 123. Comparison of Network-Level Water Consumption Results by Scenario (Hypothetical scenario Not Considered).

Table 53. Rounded Network-Level Water Consumption Values By Scenario (Hypothetical Scenario Not Considered).

	Automobile Usage	Bus Usage	Road Operation	Vehicle Service	Total Water Consumption, l/day
Baseline (Atlanta/Georgia, 2010)	21,110,000	80,034	21,462	29,466,480	50,677,060
Baseline (Extraction Included)	40,526,800	99,525	21,463		70,114,300
Washington, 2010	16,554,880	80,380	21,463	37,422,225	54,078,910
Georgia, 2030	74,133,130	67,040	24,390	32,417,640	106,642,200
Washington, 2030	76,815,400	83,560	21,461	50,189,470	127,277,840

If these aggregate results are indeed valid, these impacts of servicing and washing facilities need to be considered in addition to any impacts of fuel consumption and electricity generation on water consumption. A more accurate set of results would, however, focus on amortizing infrastructure inputs across the entire fleet of vehicles as done with road infrastructure usage water consumption and would need to be applicable to service and washing facilities within the United States, be traceable directly to the vehicles considered in this case study, as well as focus solely on water consumption instead of considering water usage for some infrastructural components.

7.8. Sensitivity Analysis: Vehicle Use-Phase Water Usage Versus Consumption

While the focus of this thesis is primarily on water consumption pertaining to vehicle and infrastructure usage, it must be noted that water consumption is only a small subset of overall water usage – the amount of water that is withdrawn from local resources during a product or system's life cycle or life cycle phase. This section will focus on including water withdrawals for fuel and energy production for vehicle usage and how the well-to-wheel water usage results compare with the existing consumption-based results for the baseline 2010 case in this model. Only per-kilometer water usage will be discussed with respect to per-kilometer vehicle use-phase water consumption.

7.8.1. Vehicle Fuel and Electricity Water Usage Inputs

As this thesis was geared towards examining individual and top-level water consumption, water usage was not extensively studied. Water usage inputs for gasoline and biodiesel were based on a public transit bus life cycle inventory as conducted by Sheehan et al (1998); these values were briefly discussed in Chapter 3. Furthermore, water usage values for some vehicle fuels and electricity generation methods are available, although not for all fuels or electricity sources; these values are summarized below in **Table 54** for this sensitivity analysis. As with the baseline case, only gasoline, ethanol, CNG, hybrid-electric, and electric vehicles will be considered; based on the almost-negligible water consumption results for bus usage, this analysis will focus instead on automobiles and *only* on water used for one kilometer driven for each vehicle type. The same vehicle efficiencies and fuel conditions as with the original water consumption analysis for the baseline case are carried over to this water usage analysis; it should also be noted that only ethanol is extracted within Georgia while all other fuels are extracted out-of-state, although state-specific water usage values are used in place of the regional water consumption values specified in the baseline case inputs.

Table 54. Water Usage Inputs for Transportation Fuels For This Analysis.

Fuel Type	Extraction Water Used, l/l fuel	Processing Water Used, l/l fuel	Distribution Water Used, l/l fuel	Reference
Gasoline	0.42 (not included in this analysis)	12.5	0.65	King and Webber, 2008 (1); Harto et al, 2010
Ethanol	94 (Georgia-specific value)	2.5	*assumed to be same as gasoline	Chiu et al, 2009
Compressed Natural Gas	1.26 (not included in this analysis)	0.62	0.156 + Fuel/Electricity For Compression	Fthenakis et al, 2010; King and Webber, 2008 (1)

A cursory examination of these values show, for these transportation fuels, how water consumption is indeed a small part of the overall outlook on water usage. For example, petroleum refining water usage is approximately 12 times greater than that of the water consumption values specified in **Chapter 6**. Similarly, water consumption for ethanol crop irrigation is approximately 14 percent that of the water usage values specified for this analysis, although this percentage may decrease even more if Georgia-specific consumption values are considered. On the other hand, there are smaller increases for natural gas with respect to water usage versus water consumption, although natural gas extraction emerges as a significant factor with respect to water usage.

Water consumption inputs for electricity generation are specified in **Table 55** for the same plant configurations and electricity source distribution for the baseline 2010 case. As with the water consumption values for electricity generation, water usage values are leveraged from various other studies and assessments on life cycle water usage in electricity generation and may not necessarily be from the same reference as that in the water consumption analyses. That said, cooling towers withdraw comparatively little water with respect to that of once-through cooling systems, so the vast majority of water usage stems from water consumed/stored in these power plants. While water consumption was traced to evaporative and seepage losses for hydroelectric power plants in the previous analyses, water flows for hydroelectric power plants are not considered as water withdrawal; as such, the same consumption values are carried over to this study (Merson et al, 2006; Torcellini et al, 2003). Thermoelectric fuel water usage inputs are shown in **Table 56**, where overall water usage for each fuel is somewhat higher than that of water consumption for these fuels**.**

Table 55. Power Plant Operation (Water Usage) Inputs for 2010.

Source	Plant Configuration	Plant Water, l/kWh	Reference
Coal-Fired	Cooling Tower, Subcritical	2.6	Gleick, 1994
NG Combined-Cycle	Cooling Tower	1.03	Fthenakis et al, 2010
Oil-Fired	Oil Cooling Tower	0.95	Fthenakis et al, 2010
Nuclear	LWR	3.2	Gleick, 1994
Wood Waste Plant	Steam Plant	1.7	Berndes, 2002
PV Solar Farm	Central Utility Average	0.022	Fthenakis et al, 2010
Wind Farm	U.S. Average	0.015	
Hydroelectric	GA Average	179.5	Torcellini et al, 2003

Table 56. Water Usage Inputs for Thermoelectric Fuels and Electricity Generation.

Source	Extraction Water Consumed, l/kWh	Process Water Consumed, l/kWh	Distribution Water Consumed, l/kWh	Reference
Coal	0.038	0.045	0.45	Fthenakis et al, 2010 (not from Gleick, 1994)
NG	0.13	0.057	0.03	
Petroleum	n/a	1.293	0	
Nuclear (Uranium)	0.038	0.124	0	
Wood Waste (Biomass)	0	0	0	(Data Deficient)

7.8.2. Water Usage Results

The above water usage inputs were applied to a separate set of instances in the SysML and calculated using ParaMagic as with the previous six case study scenarios; the water usage values for each vehicle compared with their respective water consumption value – assuming the same amount of fuel consumed for each vehicle type – are summarized below in **Figure 124** and **Table 57**. The significantly greater water usage inputs for gasoline and ethanol production result in water usage results for gasoline, ethanol, and hybrid-electric vehicles that are 5-7 times greater than that of water consumption when comparing against the 2010 base case. On the other hand, water usage for CNG-fueled vehicles is approximately 2.5 times greater than water consumption for these vehicles given the same amount of fuel consumed per kilometer traveled, while overall water usage for electric vehicle usage is only 2 percent greater than that of water consumption for EV usage with the same energy efficiencies.

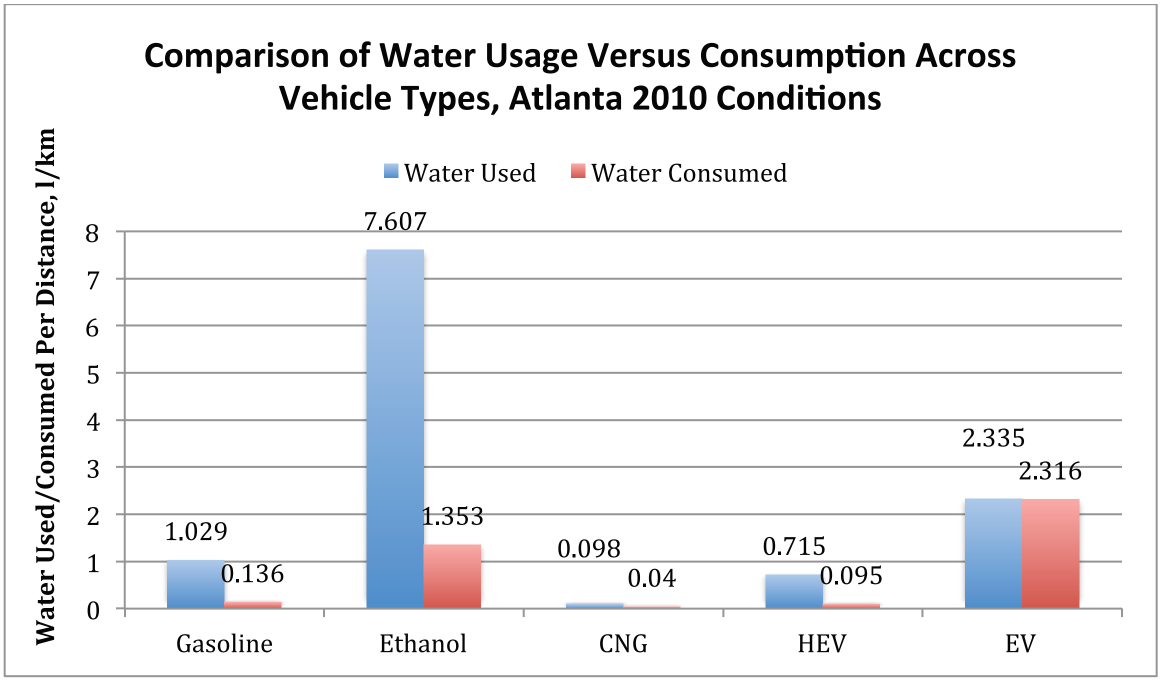


Figure 124. Comparison of Water Usage Versus Consumption Across Vehicle Types.

Table 57. Summary of Water Usage Across Vehicle Types And Comparison With Water Consumption, Baseline 2010 Case.

Vehicle	Vehicle Efficiency	WTP Fuel Water Used	Fuel Water Used, l/km	Fuel Water Consumed, l/km
Gasoline	0.0783 l/km	13.150 l/l	1.030	0.136
Ethanol	0.0783 l/km	97.150 l/l	7.607	1.353
CNG	0.0807 l/km	1.219 l/l	0.098	0.04
HEV	0.0544 l/km	13.150 l/l	0.715	0.095
EV	0.295 kWh/km	6.793 l/kWh	2.335	2.316

Accounting for overall water usage – withdrawal and consumption – for electricity generation results in modest increases with respect to the results in the baseline case; this is due to that cooling towers retain the majority of water that is withdrawn (in this case, water consumed by these power plants). However, there is some uncertainty in that many sources state that there is no water withdrawn in hydropower (Merson et al, 2006; Torcellini et al, 2003); while their rationale is that the water used for hydroelectric generation remains within the local reservoir – in this case, the hydroelectric reservoir –

and can be reused multiple times, water consumption represents a portion of overall water withdrawals or usage (King and Webber, 2008 (2)). Overall, the majority of water usage stems from power plant operation; however, the vast amounts of water withdrawn for petroleum refining results in fuel production water usage for oil-fired power plants greatly outnumbering water usage for power plant operation. Combing all of these electricity generation sources and water usage values yields a normalized average of **6.793 l/kWh** – an increase of less than one percent with respect to the 6.736 l/kWh average for water consumption. These values are summarized below in **Figure 125** and **Table 58**.

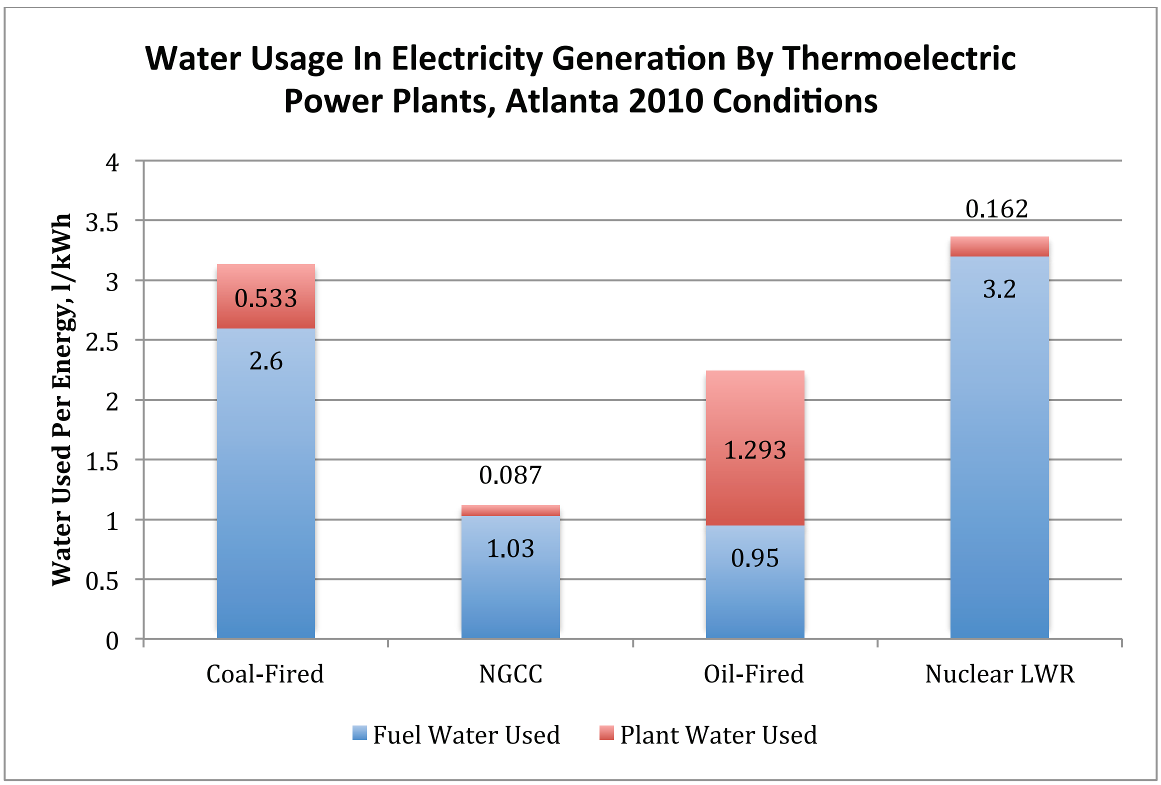


Figure 125. Water Usage Rates in Electricity Generation For Thermoelectric Plant Type, Baseline Case.

Table 58. Summary of Water Used in Electricity Generation, Atlanta 2010 Conditions (Baseline Case).

Plant Type	Plant Configuration	Plant Water Used, l/kWh	Fuel Water Used, l/kWh	Energy Output, kWh	Monthly Total Site Water, l
Coal-Fired	Cooling Tower, Subcritical	2.6	0.533	4,915,000,000	15,398,695,000
NGCC	Cooling Tower	1.03	0.087	1,356,000,000	1,514,652,000
Oil-Fired	Cooling Tower	0.95	1.293	8,000,000.00	17,944,000
Nuclear	LWR	3.2	0.162	3,031,000,000	10,190,222,000
Hydro-electric	GA Average	179.5	0	186,000,000	33,387,000,000
Wood Waste	Steam Plant	1.8	0	262,000,000	471,600,000
Total Electricity Generation, kWh				9,758,000,000	
Total Water Used, l				60,980,113,000	
Average, l/kWh				6.793	

While water usage is not the main focus of this thesis and while this analysis focuses only on individual vehicle types and not fleet-wide and network-wide impacts of water usage versus consumption, this sensitivity analysis does illustrate the significance of water usage when considering gasoline and biofuel-powered vehicles for a transportation network, where the notion that water consumption is a small part of the picture comes into play where vehicle use-phase water usage is significantly higher – 5-7 times greater – than that of water consumption. A more comprehensive analysis of water usage with respect to network-wide water consumption would certainly be needed in the future with inputs pertaining to diesel, biodiesel, plug-in hybrid, and other vehicles for other scenarios and regions.

7.9. Discussion

7.9.1. Overall Water Consumption Trends

In all of these scenarios, the largest water consumption component in terms of daily transportation network operation is water consumed from the production of fuel and electricity for automobile operation. Should vehicle servicing and washing be included in the case study results, water consumed directly and indirectly to produce electricity for supporting vehicle infrastructure also constitutes a significant portion of total daily use-phase water consumption in a transportation network. On the other hand, water consumption from the operation of road infrastructure takes up a minuscule portion of overall network water consumption, with aggregate road network values at up to 0.1 percent of the total daily water consumption value for the network's automobile fleet. The low water consumption value for road operation can be attributed to that the road network inputs are distributed throughout the entire region and are used by multiple transportation mode fleets, while the total automobile usage values are aggregated over individual vehicles. Similarly, water consumption from bus fleet usage is comparatively low despite the larger daily VKT value and lower tank-to-wheel efficiencies (in terms of fuel consumption); this is primarily attributed to the low number of buses currently being considered – in 2010, for example, only 615 buses (per MARTA's figures) and two configurations are used compared to the 2.37 million vehicles being used in these scenarios.

While calculating total monthly water consumption for electricity generation was not the focus of this thesis as the aggregate values are used to determine normalized water consumption averages, it is still important to note that water consumption for electricity generation as a whole represents an even larger chunk of local water usage (for example, 13.5 billion liters per day using Georgia's electricity mix in 2010), with the majority of water consumption traced to water required for plant operation. This is especially important given that electricity inputs are essential for the operation of any infrastructural components required for supporting a transportation or mobility network. In this model, electricity is required for operating electrical components for a region's road network and for servicing facilities; we have not even accounted for electricity required to operate power plants and fuel production networks in addition to electricity required to maintain multi-modal transportation hubs. In terms of vehicles, while this model considers only road vehicles with electric powertrains, electrical energy is also required for the usage of light rail vehicles for public transportation, and as noted in Azevedo (2010) such electric inputs represent a significant component of overall electricity consumption in a transportation network.

Similarly, for transportation fuels, the majority of water consumption from fuel production can be traced primarily to water consumed during the extraction and processing of fuels (especially in the case for extracting or recovering crude oil for petroleum) or from irrigation-related water consumption for biofuels that are grown and harvested locally. The introduction of less water-intensive crops such as switchgrass for ethanol produced and consumed in the hypothetical 2030 scenario does reduce water requirements for irrigation, while the introduction of additional biodiesel feedstock such as microalgae potentially increases average water consumption for crop or feedstock inputs. Additionally, the water consumption values for crop irrigation and feedstock process input varies greatly between production regions (although these variations are not considered in these scenarios due to lack of state-specific water consumption data), suggesting that relatively water-efficient ethanol production in one region due to lower irrigation requirements and lower evaporation rates

Based on all of these results, it is important to note that these water consumption estimates can vary wildly depending on region and technology, as shown in the previous six scenarios that focused on Georgia's or Washington's electricity mixes and fuel conditions for 2010 and 2030 in addition to implementing dry cooling and other emerging plant technologies for the hypothetical scenario. Furthermore, as evaporation rates vary by state to state as shown in Torcellini et al (2003), a given electricity generation grid may have a larger water consumption value in one given region and a relatively low value in another. This means that location and technology are potentially the key factors for whether or not to implement plug-in hybrids and electric vehicles in a given transportation system or urban region. In particular, when considering water consumption values for power plant operation, the vast majority of water consumption comes from hydroelectric power and associated reservoirs. Removing this electricity generation source drastically reduces overall water consumption for Georgia's electricity mix as shown in the hypothetical scenario.

7.9.2. Water Consumption Trends in Individual Vehicle Modes

For both the automobile and bus fleets considered in this network, the water consumption for the use-phase of these vehicle modes is primarily traced to the production of the fuel being consumed over a given traveled distance. For this model framework, this is primarily governed by the vehicle's energy or fuel efficiency, which generally varies depending on fuel or vehicle configuration. In the sensitivity analysis on vehicle efficiency between 2010 and 2030 conditions, improving fuel and energy efficiency (read: lowering the vehicle efficiency values) based on listed projections ultimately decrease use-phase water consumption.

Despite the water-intensive production process for the coolant mixtures and lubricants used in this vehicle fleet (in this case, made primarily out of ethylene glycol/water and petroleum, respectively), water consumption from fluid usage represents only a small percentage (about one to two orders of magnitude lower than that of fuel-related water consumption) of the vehicle usage water consumption in this model. Of course, this excludes other fluids used in the vehicle's powertrain and chassis components – such as hydraulic fluid for braking and steering or refrigerant for a vehicle's climate control system – but this low level of water consumption is due to the service intervals between oil changes and coolant flushing (evaporative losses from these fluids is not considered for these vehicle types in this model). There is, however, no consistent way to validate the per-distance water consumption calculation for these auxiliary flows, as no structures exist for assessing per-distance material consumption of such flows. This model's parametric framework assumes that the fluid is gradually "consumed" over a given service interval – essentially, a straight-line depreciation of the vehicle's fluids in terms of usefulness. As the focus of this thesis is to examine top-level water consumption components – for each vehicle, for each fleet, and for the entire network – not much development has been made in devising a robust calculation method for the water consumption that properly accounts for auxiliary fluid usage for a given traveled distance.

Another driving factor in vehicle usage water consumption pertains to the average traveled distance for a given transportation network. As a widespread urban region that supports primarily passenger vehicle travel, Atlanta has a relatively high automobile VKT average (44.9 km in this study); reducing this VKT average to 35 km, as shown in the scenarios implementing Washington State's energy and travel conditions while maintaining the same vehicle share, decreases overall daily water consumption from vehicle usage by approximately one-fifth that of the baseline total usage water consumption value as described in **Figure 126** and previously in **Table 43**. As such, consolidating urban regions such that commercial, residential, and industrial elements are located within a closer proximity to each other can potentially reduce automobile travel and ultimately total usage-related water consumption.

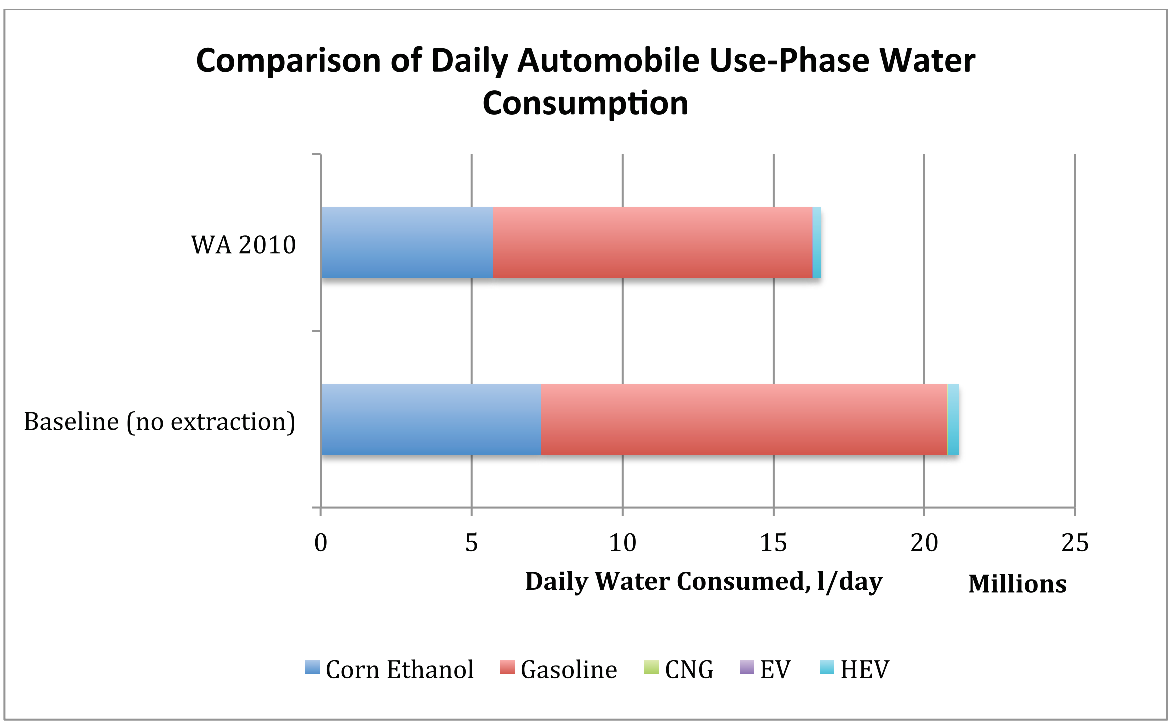


Figure 126. Comparison of 2010 Total Automobile Usage Water Consumption Per Day.

CHAPTER 8

VALIDATION

8.1. Overview

The above individual and aggregate results for the six scenarios considered in the previous several sections can now be compared against each other in order to determine overall water consumption trends and main driving factors in transportation-related water consumption for vehicle usage and supporting infrastructure. That said, such results are not terribly meaningful without assessing the validity of the model and supporting methodology with respect to existing assessing frameworks and life cycle inventories for fuel production and vehicle usage.

The validation of this model and supporting methodology will be applied to the baseline results while projected estimates will also be examined; these components will be examined using the **validation square tool**, which is a synthesis of research validation process components in terms of evaluating a design or system based on its usefulness, effectiveness, and efficiency in quantitative and qualitative terms (Pederson et al, 2000); an example of the validation square is shown below in **Figure 127.** By examining this system model in terms of theoretical and empirical validity in terms of model structure effectiveness, the intent is to determine whether this model is indeed consistent and whether the model's underlying framework and analytical structure can be justified and valid for a larger range of applications.

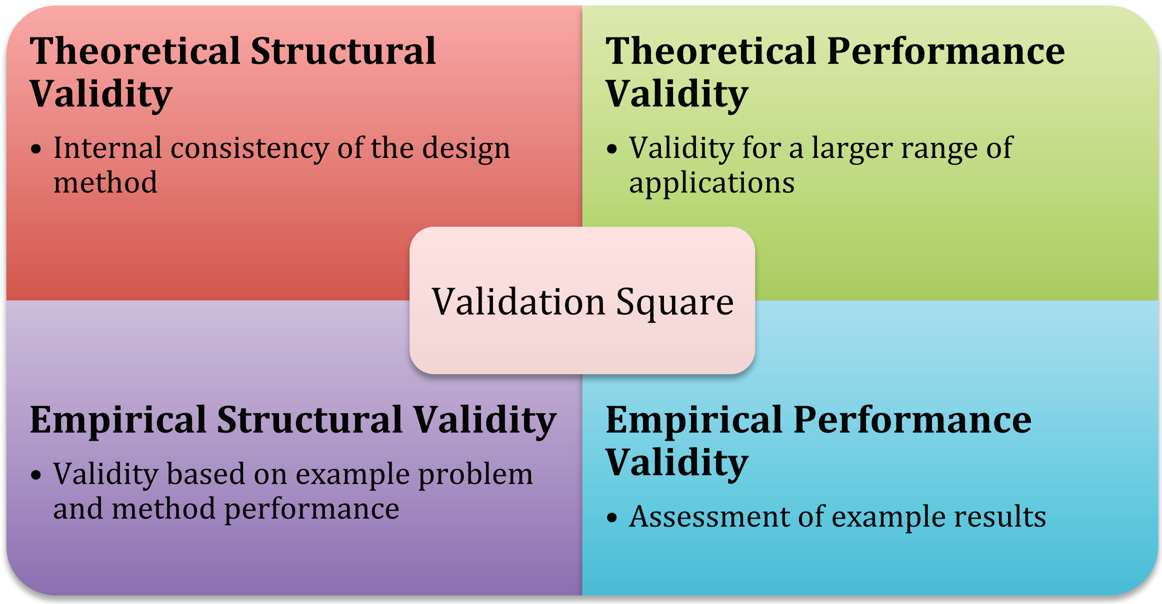


Figure 127. The Validation Square.

8.2. Theoretical Structural Validity: Internal Consistency

The first element in the validation process for this model is to consider whether the underlying methodology or framework for this model is internally consistent – in this case, it is necessary to ensure that the structural and analytical elements in this model meets the requirements initially set forth for this system model and engineering analysis components. While verification of design requirements in the engineering design process is required to ensure that the developed concept and embodied design matches the demands and wishes of key stakeholders and the design team itself, the requirements verification in this analysis model pertains to ensuring that the analyses and associated elements for transportation modes and infrastructure satisfy the initial requirements pertaining to how to analyze one or more metrics or pertinent values as well as to what components should be analyzed, in addition to other constraints and requirements such as scope and system boundary.

8.2.1. Consistency with Individual Component Requirements

The requirements verification process can be facilitated and streamlined by the implementation of cross-cut relationships within SysML in which certain structural and analytical elements in this model can satisfy corresponding requirements by allocating the former to the latter. The next few sections outline how each of the key analytical and structural components in this model can be allocated to certain requirements on a component and aggregate level.

The validation of top-level components and domains in this model with respect to system-level requirements is shown below in **Figure 128**, with requirements satisfaction between these elements specified as a <<satisfy>> relationship from these top-level structural objects to packaged requirements. For the most part, the top-level components do adhere to the system-level requirements, such as for the Mobility Network structural block satisfying the need to implement a multi-modal transportation network based on reusable and traceable objects and parameters; that said, as this system model is ultimately limited to considering road transportation modes, not all of the requirement has been specified as the final iteration of this model does not extend to rail, air, or maritime transportation modes. On the other hand, the analysis model adheres to the constraint specified in the model pertaining to considering only water consumption components associated with the structural elements in this model; on the other hand, while the bulk of the case studies has focused on local water consumption, one of the scenarios has included water consumption elements – specifically for that of fuel extraction – that may not pertain to local water impacts, although this is in an attempt to provide a more comprehensive outlook of transportation usage water consumption. The structure specified in this model also ultimately adheres to the omission of upfront and upstream water consumption components such as for facilities construction.

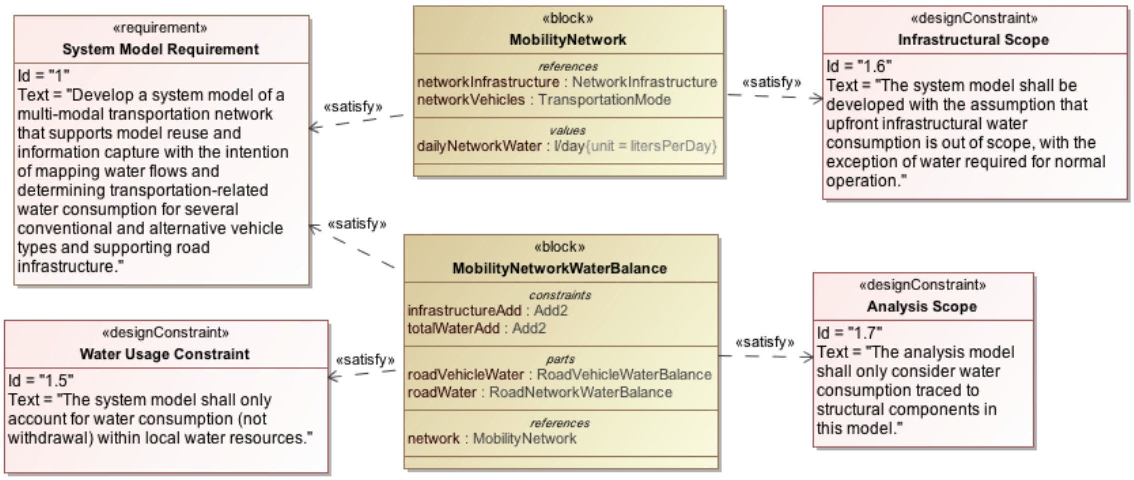


Figure 128. Top-Level Requirements Verification Via Allocation Relationships.

Overall, domain-level and component-level requirements are generally satisfied when examining structural and analytical components that pertain to these specifications. **Figure 129** illustrates the requirements allocations for electricity generation, where the requirements for specifying the structural breakdown and input data for thermoelectric and renewable energy generation are satisfied by the structural objects depicting electricity generation components and referenced inputs; that said, one of the requirements pertaining to thermoelectric plant specification is ultimately violated for one of the case studies in this model where additional emerging technologies are considered for power plant generation. Similar allocations can be made for the fuel pathway structure in **Figure 130**.

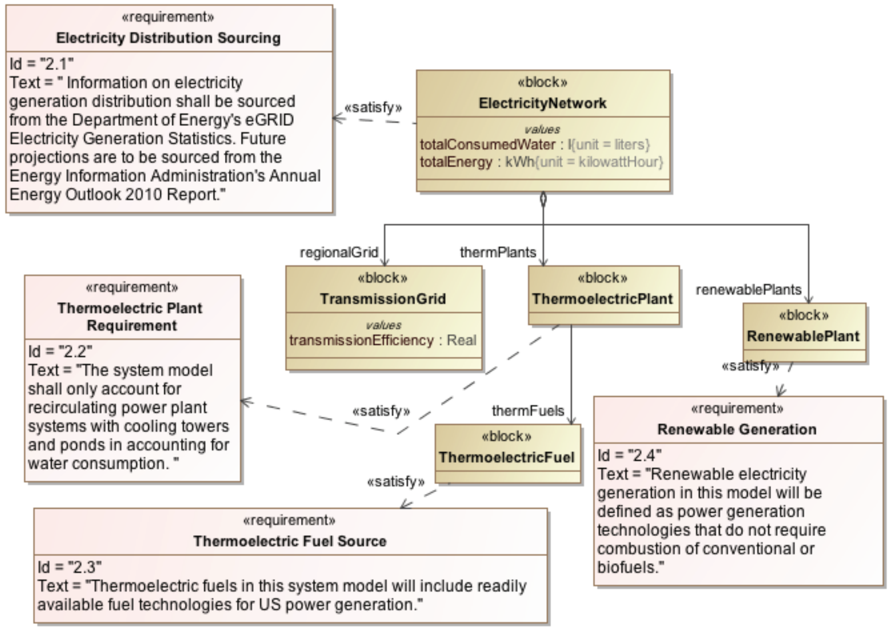


Figure 129. Electricity Generation Modeling Requirements Validation and Allocations.

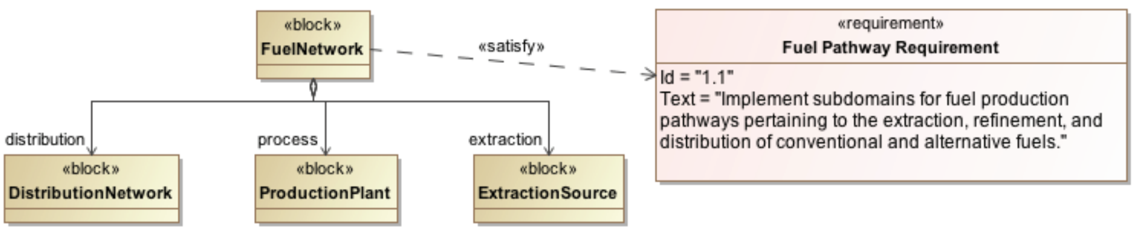


Figure 130. Fuel Pathway Modeling Allocations.

Analysis requirements and constraints can also be allocated to the top-level analysis blocks, such as the <<satisfy>> relationships between vehicle usage analysis requirements and corresponding blocks in **Figure 131**. The analysis block breakdown for each of the vehicle technologies considered in this model, as shown in Chapter 5, adheres to the requirements specifying that water consumption from vehicle operation – either as indirect consumption from the production of material flows or direct water inputs – is the only set of inputs and target values to be considered; for battery electric vehicles and PHEVs, the requirement that the vehicle usage analysis also consider electric powertrain efficiencies is satisfied. That said, one of the requirements specifying the inclusion of usage inputs from vehicle accessories and other auxiliary inputs has not been satisfied;

while accessory inputs in terms of auxiliary requirements for vehicle electronics was included in initial versions of the model, this was ultimately omitted in favor of assessing only fuel consumption and vehicle fluid consumption inputs using the values specified from other life cycle models and vehicle assessments.

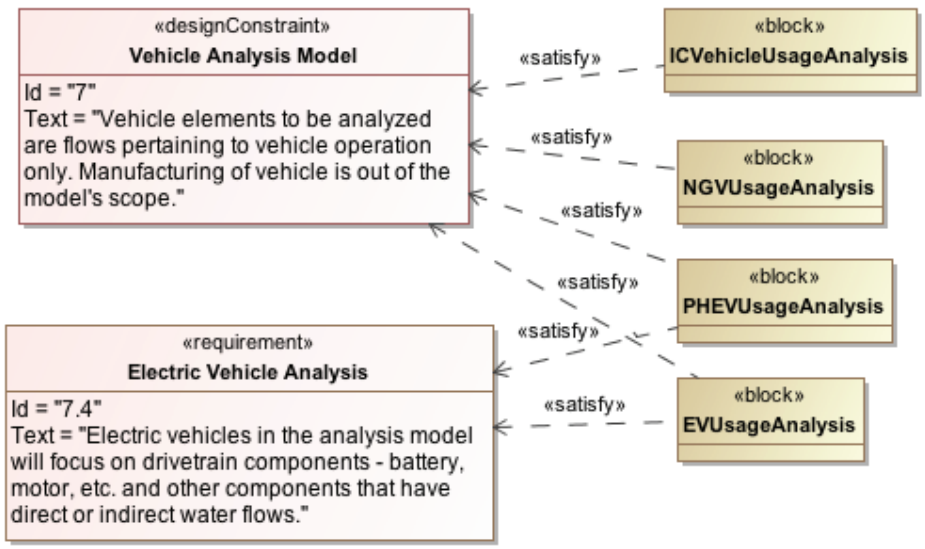


Figure 131. Vehicle Usage Analysis Requirements Validation.

Ultimately, most of the requirements set forth in this model have been satisfied with the analysis and structural breakdown specified in this thesis, although some requirements were violated in the attempt to explore the reusability of the system model for additional conditions and to provide a more comprehensive outlook of water consumption for a transportation system's usage. Additionally, some requirements pertaining to the implementation of certain components such as auxiliary vehicle electronic inputs could not be properly implemented in this model, as there is no existing framework for including these extra inputs, while many of the other requirements have been developed based on the initial problem statement and questions as well as on existing methodologies and studies. All in all, the model's primary analysis and structural components are internally consistent with t he specifications and demands set forth in the model's requirements.

8.3. Empirical Structural and Performance Validity: Method Validation

The next step in the validation process is to ensure that the model's analytical framework – structural performance parameters and constraint properties as well as target values – are performing as expected and whether they satisfy the analysis requirements. In this chapter, some examples of the model's repeatability have been outlined that are fairly consistent with Given the lack of existing network-level assessments that can be used to validate the quality of top-level results for this model, this validation step will examine individual vehicle types as well as individual energy pathways (electricity and transportation fuel networks) and compare with existing water consumption data from other sources.

For this example, a plug-in hybrid electric vehicle (PHEV) – which is one of the vehicle types specified as part of the network's automobile fleet – is assessed, along with any associated energy pathways and any other pertinent flows in which concrete information or consumption results are available. While there is no widespread implementation of plug-in hybrid vehicles, several models are currently being developed and distributed in selected areas of the United States, such as the Chevrolet Volt that will be used in this example (**Figure 132**). As a PHEV, the Chevrolet Volt combines a 1.4-liter 4-cylinder internal combustion engine along with a 149kW electric powertrain, in which the IC powertrain serves as a range-extender combined with a 55kW electric generator that is used to directly power the electric motors whenever the battery is depleted of charge; the electric powertrain itself contains a 16 kWh battery with a theoretical range of 40 to 80 km (Wikipedia, 2010). The pertinent efficiency values for this vehicle are shown in **Table 59** along with additional auxiliary fluid values specified by Chevrolet (Chevrolet, 2010), where the fluids to be included are coolant mixtures for the vehicle's engine and battery along with motor oil; it is assumed that the same base materials for these auxiliary flows as specified in the above scenarios (petroleum for engine lubricant and ethylene glycol for engine coolant) are used along with manufacturer-recommended servicing intervals. In this example problem, only per-distance water consumption pertaining to the vehicle's use-phase will be explored, since: (1) comparison results from previous studies examined vehicle usage water consumption per mile traveled, and (2) the daily VKT/VMT varies significantly by region and daily water consumption results cannot be easily verified. Additionally, the electricity mix for Georgia in 2010 conditions – with fuel production values included – along with gasoline water consumption data as defined previously in the model are used as energy inputs. For this individual scenario, it is assumed that water consumption will be limited to in-state fuel production.

Although aggregate daily water consumption is not considered for this example problem, it should be noted that individual vehicle analyses in this model – as well as lower-level fuel analyses and water balances for infrastructural usage – can be calculated independently without a need to populate any non-pertinent input values, although only ancillary outputs for the vehicle analysis block/instance will be calculated.

Figure 132. The Chevrolet Volt (Source: General Motors).

Table 59. Vehicle Efficiency Values for the Chevrolet Volt.

	Fuel Efficiency, l/km	**Energy Efficiency, kWh/km**	**Reference**
Electric-Only Mode, EPA	0.0253	0.225 *(0.36 kWh/mi)*	Wikipedia, 2010; EPA Vehicle Label
Electric-Only Mode, GM	----	0.4-0.8 (*usable: 0.26-0.52)*	Wikipedia, 2010
Electric-Only Mode, Overall		0.4	Harto et al, 2010
Gasoline-Only Mode	0.064	----	EPA Vehicle Label
Combined Mode	0.025		EPA Vehicle Label

Table 60. Vehicle Efficiency Values for the Chevrolet Volt (Chevrolet, 2010).

	Listed Amount, l	**Service Interval, km**	**Remarks**
Engine Oil (With Filter)	3.5	24000	Service interval at 15,000mi (24000 km)
Engine Coolant Mixture	6.3	240000	50/50 Mixture of DEX-COOL and de-ionized water
Battery Coolant Mixture	6	240000	50/50 Mixture of DEX-COOL and de-ionized water
Fuel Capacity	35.2	n/a	

As the above listed values and the overall specification of the Chevy Volt matches the description of "PHEV" in the model due to the fact that the Volt contains both IC and EV powertrains, this vehicle example can be easily defined as an instance of the PHEV system block, as shown below in **Figure 133**. Similarly, the associated energy and auxiliary flows (gasoline, electrical energy, engine and battery coolant mixtures, and engine oil) are separately defined or leveraged from instances created for the Georgia 2010 extraction-included scenario for Atlanta.

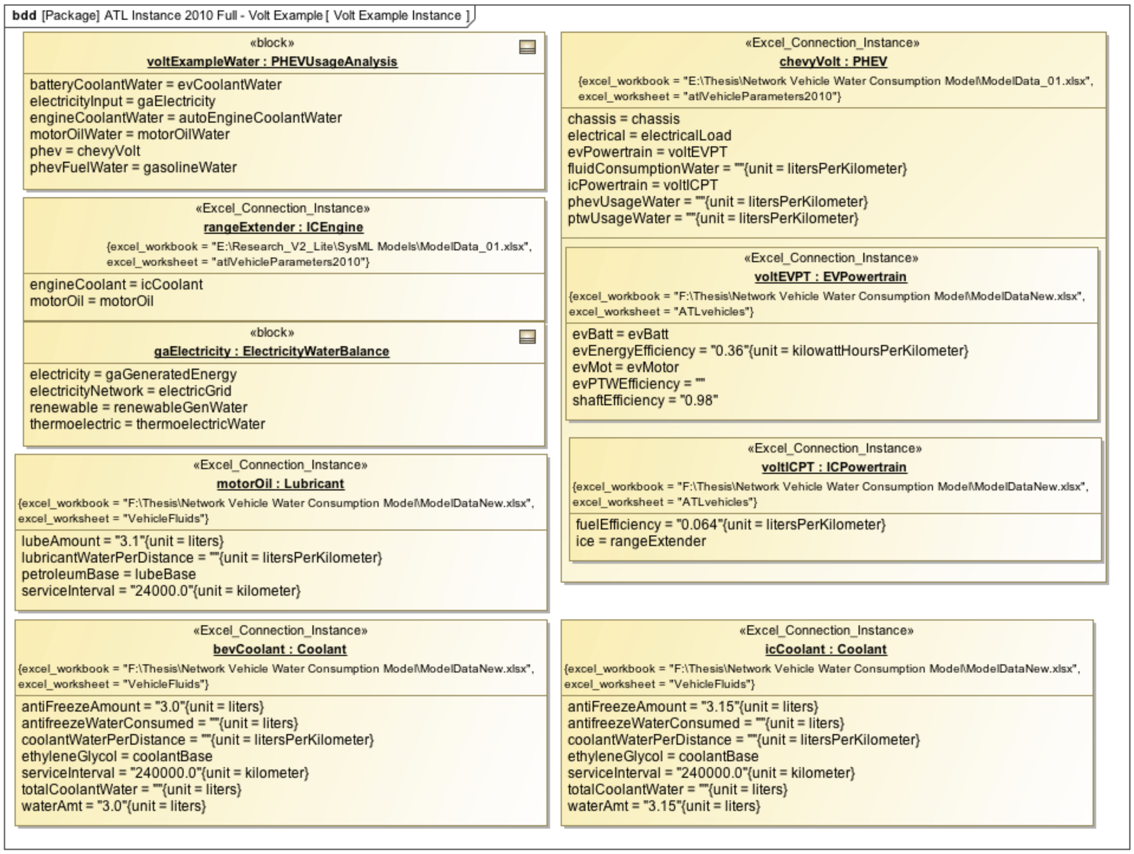


Figure 133. Instance Specification for Chevrolet Volt Example Problem.

8.3.1. Electricity Mix Water Consumption Calculation and Validation

The electricity mix water consumption value to be inputted as part of the vehicle's use-phase was previously calculated in Case 6, the fuel extraction-included scenario for Atlanta using Georgia's monthly electricity mix in 2010 conditions. As explained before, these electricity output values were obtained from the Energy Information Administration's State Energy Profiles for Georgia and verified with the Environmental Protection Agency's eGRID model. Fuel production values for electricity generation and plant operation are leveraged from the input values specified for this case. Normalized water consumption based on these input values are calculated based on the parametric framework and water balance equations specified in Chapter 5 and are compared to existing water consumption averages from previous assessments and studies; as these equations are examined in great detail in that chapter, they will not be replicated in this section.

When compared against normalized water consumption figures for electricity generation in King and Webber (2008, 2) and Torcellini et al (2003) this number is near the high-end estimate of average water consumption for electricity; this is mainly due to the large water consumption values that are somewhat traceable to hydroelectricity (**Table 61**). Furthermore, while the normalized average in this case study includes hydroelectric and wood waste power generation, the values calculated in King and Webber (2008, 2) reflects mainly on thermoelectric power generation and associated fuels. Furthermore, the water consumption calculation in this model accounts for transmission-related losses in electricity output –something that is not specified in the previous two estimates.

Removing the water consumption factor from evaporative losses in hydroelectric power generation yields an average value of 2.92 l/kWh, which has an error of 18.6% with respect to the value in King and Webber (2008, 2) – a significant deviation – that can be partly explained by differing water consumption values pertaining to thermoelectric plant configurations and the inclusion of biomass plants. A direct comparison with the average site water consumption value for Georgia as catalogued in Tortellini et al (2003) places the calculated water consumption average in this model near the published value of 6.246 liters per kilowatt-hour with an error of 7.8%, which suggests that the electricity network and associated parametric layout described in Chapter 5 is somewhat valid for state-by-state comparisons.

Table 61. Comparison of Normalized Electricity Generation Water Consumption Values.

Electricity Generation Reference	Low Water Consumption, l/kWh	High Water Consumption, l/kWh
NREL Estimates – U.S. Averages (Torcellini et al, 2003; Harto et al, 2010)	1.779	7.5708
King and Webber, 2008 (2)	2.461	
NREL Estimate – Georgia Site Water Average	6.246	
Georgia, 2010 Conditions	6.736	
Georgia, 2010 Conditions (Hydroelectricity Removed)	2.919	

8.3.2. Vehicle Usage Water Consumption Calculation and Validation

The above electricity water consumption average, along with existing water consumption values from gasoline production, was applied to the PHEV instance in order to obtain well-to-wheel vehicle usage water consumption values, with the results shown below in **Figure 134**. As the Chevrolet Volt can switch between EV and IC powertrain systems and also operate on electric mode alone, the results were separated based on EV mode usage, gasoline mode usage, and combined cycle usage. The EV powertrain in the Volt consumes the majority of water in the Volt's use phase, with a water consumption value approximately 91 percent of the vehicle's combined-mode usage. Water consumption from auxiliary fluid usage (evenly distributed across the fluids' respective service intervals) still maintains a very small percentage of total water consumed per vehicle-km traveled; however, given the introduction of water as part of the battery's coolant mixture and the implementation of longer service intervals, this value is even lower than the 0.003 liters per km calculated in the previous scenarios.

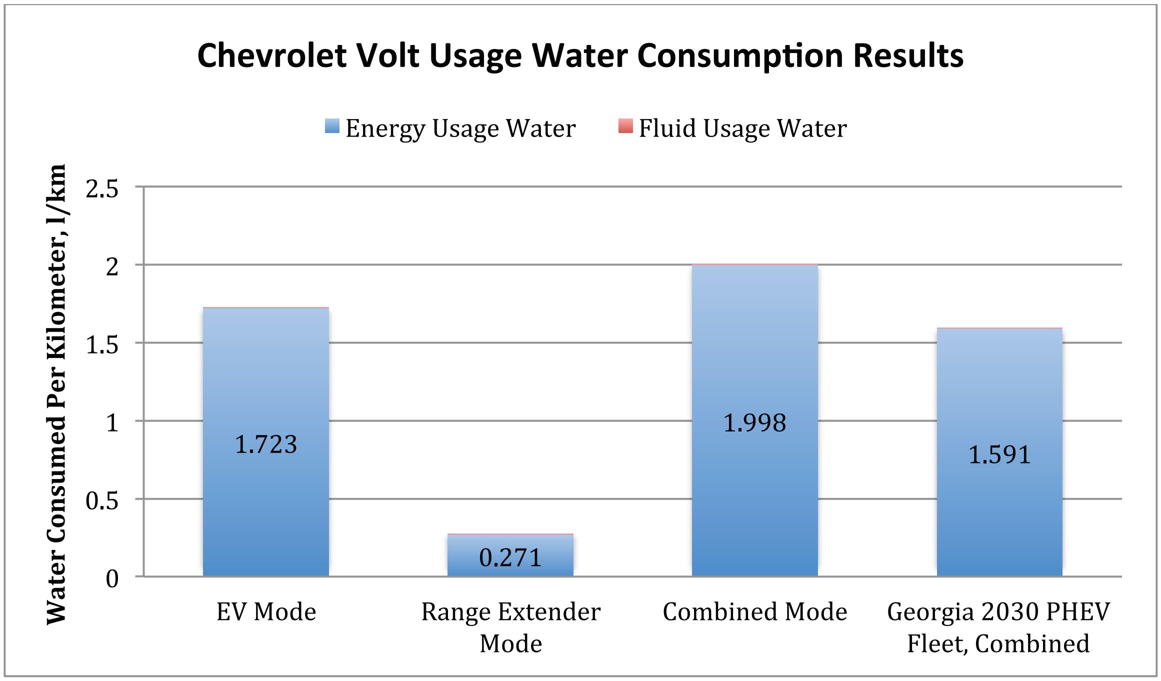


Figure 134. Comparison of Example Results.

Compared to the results in the previous 2030 scenarios, water consumption for driving the Chevrolet Volt one kilometer in combined-mode conditions is 28 percent higher than the projected PHEV fleet's average water consumption value of 1.5 liters per kilometer; that said, since the electricity generation water consumption averages for these two cases are very similar, the deviation can be attributed to the higher-efficiency powertrain components in PHEVs projected for 2030 (in this case, for the IC powertrain since the energy efficiency values for both cases are approximately the same) and not to any errors from the model's analytical framework.

However, when comparing these results with respect to existing studies on PHEV usage, these values are significantly larger than those used. Compared to the EV mode water consumption value as estimated for a PHEV fleet in King and Webber (2008, 2), use-phase water consumption in this example problem is 1.6 times greater than that of the average PHEV use-phase water consumption value as summarized in **Table 62** (King and

Webber, 2008 (2)). That said, the water consumption calculation method in the model and of that in King and Webber (2008, 2) is essentially the same, albeit with a different powertrain efficiency that accounts for the drivetrain and motor components in addition to that of battery charging. Given that the energy efficiency values for both this example and the assessment in King and Webber (2008, 2) are very similar, the deviation in calculated values can be traced to water consumed in electricity generation (as mentioned in the previous sub-section) as well as the inclusion of water consumption from the production and usage of coolant and engine oil. Implementing the non-hydroelectric water consumption value to this example would decrease this error from 163% to approximately 1.12 percent.

Table 62. Comparison of Use-Phase Water Consumption Values and Associated Input Parameters.

<table>
<tr><th>Assessment Type</th><th>Energy Efficiency, kWh/km</th><th>Electricity Generation Water Consumption</th><th>Component Efficiency, %</th><th>Use-Phase Water Consumption, l/km</th><th>Error, %</th></tr>
<tr><td>Chevy Volt Example</td><td rowspan="2">0.225</td><td>6.736</td><td rowspan="2">85.8%</td><td>1.726</td><td>163</td></tr>
<tr><td>Chevy Volt Example (Hydroelectricity removed)</td><td>2.919</td><td>0.765</td><td>1.12</td></tr>
<tr><td>King and Webber (2008, 2) PHEV Fleet</td><td>0.21</td><td>2.461</td><td>68%</td><td>0.757</td><td>0</td></tr>
</table>

It should be noted that the above comparison of calculated use-phase water consumption is based on EV powertrain operation only. However, the fuel-related water consumption from the PHEV's IC components can be separately compared with the results for gasoline-powered vehicles – while the fuel efficiency value for the Volt's IC powertrain is vastly different from the gasoline fleet fuel efficiency average of 0.115 l/km used in King and Webber (2008, 2) and that differing fuel extraction water consumption values were used, the calculation method for both examples is the same (King and Webber, 2008 (2)).

8.3.3. Validation of Vehicle Mode Water Consumption Trends

While network-level daily water consumption values are not available in preceding use-phase evaluations for passenger vehicles, this example problem can be expanded to consider whether the overall trends in water consumption between individual vehicle modes are consistent with those of previous studies and assessments. For example, in both of their assessments on conventional and alternative vehicle modes, King and Webber have concluded that PHEVs in electric mode consume three times more water than their gasoline-powered counterparts during their use-phase via a direct comparison between a given PHEV fleet average of 0.21 kWh/km and a fuel economy average of 20.84 mpg (0.115 l/km). In a subsequent assessment, gasoline vehicle usage water consumption was compared with those of ethanol and biodiesel vehicles as well as other vehicle types such as CNG-powered automobiles and electric vehicles, with corresponding fuel efficiency values and water consumption estimates summarized in **Table 63**. As differing data sources are used between this model and the assessment in the King and Webber papers, only general trends will be considered. As with the results in this model, only low-range values will be considered. From this assessment, diesel and CNG vehicles consume 72 and 86 percent of the baseline water consumption value for gasoline vehicles as 0.165 l/km, where EVs consume 3.4 times more water than their gasoline-powered counterparts during their usage per kilometer. For biofuels, water consumption for ethanol and biodiesel vehicles are 18.64 and 8.6 times greater than that of gasoline vehicles, respectively.

Table 63. Low-Range Water Consumption Values for Individual Vehicle Modes from King and Webber (2008, 1).

Vehicle/Fuel Type	Vehicle Fuel Efficiency, l/km	Energy Efficiency, kWh/km	Fuel Water Consumed, l/km	Water Consumption Ratio w/ Gasoline
Gasoline	0.115	----	0.165	1
Diesel	0.083	----	0.118	0.72
Corn Ethanol	0.156	----	3.076	18.64
Soybean Biodiesel	0.0915	----	1.419	8.6
CNG	0.115	----	0.142	0.86
EV	----	0.2313	0.568	3.44

These values were compared to the values presented in the extraction-included scenario for Atlanta using Georgia's electricity mix and fuel conditions for 2010; these values are reiterated in **Table 64** along with biodiesel-powered vehicles that were not considered in the actual case study. Note that in the case study there are several discrepancies: for biodiesel vehicles it was assumed that biodiesel would be directly used in diesel vehicles, and ethanol vehicles in the Annual Energy Outlook report were assumed to be flex-fuel vehicles. For the results in this scenario, CNG vehicles consume the least water, with electric vehicles consuming the most; otherwise, the overall trend of use-phase water consumption follows that of King and Webber (2008, 1) in that ethanol vehicles consume more water than that of biodiesel vehicles.

Table 64. Vehicle Mode Usage Water Consumption Values Calculated Using the System Model.

Vehicle/Fuel Type	Vehicle Fuel Efficiency, l/km	Energy Efficiency, kWh/km	Fuel Water Consumed, l/km	Water Consumption Ratio w/ Gasoline
Gasoline	0.0783	----	0.332	1
Corn Ethanol	0.0783	----	1.353	4.1
Biodiesel	0.0598	----	0.833	2.51
CNG	0.0807	----	0.04	0.121
EV	----	0.295	2.263	6.82

A quick look at the overall water consumption trends shows significant deviations from existing vehicle usage assessments; in this model, electric vehicles consume 6.8 times more water compared to their gasoline counterparts, although this high water consumption value has been previously found to be due to water evaporated from hydroelectric reservoirs. On the other hand, while ethanol-fueled vehicles consumed 18.6 times more water than those of gasoline vehicles in King and Webber (2008, 1), ethanol vehicles consume only 4.1 times more in this model. Using the fleet average fuel efficiency value from King and Webber's study, water consumption for ethanol vehicle usage is still well below the low-end value in the previous study at approximately 8 times that of gasoline vehicle water consumption. However, it must be noted that the extraction-related water consumption value used in this scenario for gasoline production increases the baseline gasoline vehicle usage water consumption value twofold, while in King and Webber (2008, 1) water consumption from gasoline extraction is estimated to be somewhat lower at 1.6 liters of water per liter of gasoline compared to the 2.5 l/l used in this model.

Similar deviations can be seen for the water consumption results between CNG vehicles and gasoline vehicles; initially, in this model the difference in water consumption between CNG and gasoline vehicles is much more apparent that that in King and Webber (2008, 1), with a CNG usage-gasoline usage ratio in this model of 0.09 compared to 0.86 in the King and Webber assessment. A closer look at the underlying methodology for CNG vehicle usage in King and Webber (2008, 1) shows that the existing CNG usage water consumption value is calculated using standard cubic feet instead of equivalent gasoline gallons (with a conversion factor of 121.5 SCF equal to 1 gallon of gasoline in the study) – a key deviation in these initial calculations was that different energy output values for CNG were used; while this model initially assumed that the energy output for CNG was a quarter of that of petroleum gasoline, the normalization of CNG to equivalent gasoline gallons and efficiency in King and Webber (2008, 1) uses the same energy content as gasoline was used. Based on these deviations, the model inputs for the case study were calibrated to account for this assumption.

However, the basic analytical framework for calculating CNG vehicle usage water consumption is similar to that of gasoline and biofuel-powered vehicles; in that perspective, the analytical framework in this model is valid, although the data handling in this model is very different from that of the baseline assessment (and potentially incorrect).

8.3.4. Validation Assessment

The significant deviations in electricity generation and fuel production water consumption calculations and associated electric vehicle usage water consumption estimates highlights one major obstacle to ensuring that the model is indeed valid from an empirical viewpoint: the quality and consistency of input parameters and variables. A model and its scenarios are only as good as the data that is used as inputs, and in this case there are some serious issues regarding the applicability of the results to the region being specified. For example, much of the data in this model and in the presented literature review has been based on a national inventory of fuels or electricity sources as well as for average values based on nationally-defined vehicle fleets, while some other inputs are completely foreign (such as the material and energy consumption data in Spielmann et al (2007)) or pertain only to specific conditions (such as the seasonal input of road salt). For example, hydroelectricity evaporation inputs specified for the above case studies pertain only to a sample of hydroelectric plants in certain regions or states across the United States in which only the most productive plants were considered (Gleick, 1993; Torcellini et al, 2003) and that there has been no research in properly allocating evaporation and seepage values directly to electricity (the researchers instead point to the fact that without the implementation of hydroelectric dams and reservoirs the water consumed in evaporation can ultimately be used for other purposes (Torcellini et al, 2003)).

Most of the fuel production water inputs and consumption values have also been based on national averages from a sample group of fuel extraction sites and processing plants; only the water consumption data for ethanol production can be attributed to regional conditions (Wu et al, 2009). Furthermore, the presentation of input data (or results in the case of each assessment in terms of water consumption) for fuels and energy sources across these studies is fairly inconsistent with the inclusion of low-high ranges in addition to average values; while the case study in this model uses low values, there is no guarantee that these low-end values (mixed in with average values) may actually apply to Atlanta or the states' electricity or fuel production/distribution networks for these scenarios. On the other hand, initial fuel efficiency values as specified by GREET were based on a wide range of light vehicles and were ultimately not consistent with the estimated and projected vehicle performance values defined within the VISION model and the Annual Energy Outlook 2010 report; even with the more consistent fuel efficiency inputs, there is no guarantee that the vehicle efficiencies are necessarily applicable for a given region or network as these values are based on a nationwide assessment of existing road vehicle configurations. Similarly, The only set of spatially-explicit values that can be specified pertain to the buses in this network, in which bus models and respective efficiencies can be clearly specified for the Atlanta transportation network.

Ultimately, the above example problem does show that the underlying analytical framework for assessing use-phase water consumption for individual vehicle modes and electricity generation is fairly valid, with average results for electricity generation closely mirroring existing average values – given the proper scope of energy sources, as shown with the discrepancy of hydroelectric power in the above example – and use-phase calculations for vehicles operating either using IC or EV powertrains being somewhat consistent depending on the fuel production and vehicle efficiency values used. That said, the lack of consistent or spatially-explicit data on water consumption for material and energy flows in this model and associated case studies, along with wildly varying inputs between this model and existing vehicle usage assessments inhibit having a full outlook of whether this model is actually valid for regional conditions. Furthermore, as the previous studies and assessments leveraged for and compared with this model compare water consumption for a specified unit distance and leave out auxiliary flows and supporting infrastructure, there is currently no way to validate the infrastructural section of this model or network-level water consumption for a given time period.

8.4. Theoretical Performance Validity: Usefulness to Additional Applications

The last step in the validation process is to consider, based on the model's underlying framework and the previous four scenario results, whether the model and analysis framework can be used for other assessments or transportation-related applications. In doing so, the underlying structure of the model and its potential for expansion or augmentation for other assessments is examined, in a general conclusion can be made as to whether this can actually be done.

In terms of the model results, this step in the process will also include determining whether these results can actually be used as a part of the decision-making process for implementing alternative fuel infrastructure and vehicles into an existing transportation network – essentially, considering whether these results lend to evaluating the resilience of current fuel and energy pathways as well as water resources to support such network infrastructure.

The four scenarios detailing specific electricity generation and fuel conditions as well as travel statistics for Atlanta and Seattle in 2010 and 2030 highlight the model's relative flexibility in assessing multiple variations of a given transportation network, thanks to the inclusion of separate model instances that can store unique values for a given parameter or structural element. The latter two scenarios that focus on varying vehicle performance and market distribution parameters – as well as assessing for more varying conditions pertaining to electricity generation – do show that this model can be used to assess and plan out potential future conditions in addition to evaluating what is available in a present transportation system. That said, the analytical breakdown and allocation of water consumption metrics for each object in the transportation network model is heavily based on what water consumption data for each fuel and energy source is available from previous assessments, and ultimately any water consumption data that incorporate more granular values than the parameters specified in this model would ultimately require expanding the model or combining these values to accommodate such inputs.

However, while it is possible to expand the model to incorporate additional water consumption analyses or additional material and energy flow parameters due to the object-oriented nature of the SysML-based model, one issue to consider is whether the model can be expanded to incorporate other analyses in terms of evaluating environmental impacts for other material or energy flows – for example, assessing carbon dioxide emissions for these vehicles and associated network infrastructure (which has been explored before in Azevedo (2010) and numerous transportation life cycle models such as in the GREET model). This is the impetus for decoupling analytical elements from this model from the model's objects depicting individual vehicle types, infrastructure, and corresponding domains; by populating the structural elements *only* with pertinent performance metrics, mechanical or structural part compositions and leaving assessment-specific constraints to dedicated analysis blocks, a system model such as the one described in this thesis can ultimately be expanded to consider other energy or flow analyses or balances for this transportation system. **Figure 135** details an example in which the model can be easily expanded to include additional analyses, in which a separate analysis block pertaining to evaluating usage emissions is defined such that it references existing values and properties of the ICVehicle block without significantly altering the model's structure. While this expansion of analytical components will not be elaborated in this thesis, the modular nature of the model's internal elements allows for such expansion in future versions of this model.

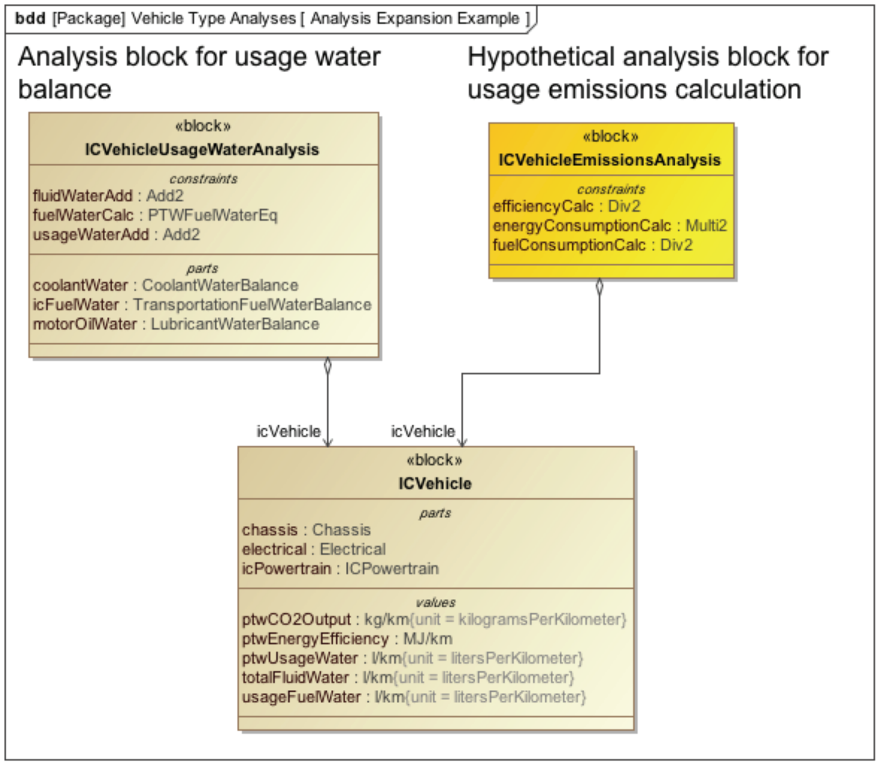


Figure 135. Potential Expansion of Use-Phase Analyses in Current Model (Hypothetical Analysis Block shown in Yellow).

Similarly, with the inclusion of instance elements, existing structural blocks can serve as a template for expanding the model or scenarios to other vehicle modes that include common powertrain components, or for specifying additional fuels for these assessments. An example of this would be specifying hydrogen as a transportation fuel as shown in **Figure 136** where the same structural and analysis framework for assessing water consumption for compressed natural gas can be leveraged to evaluate water consumption or usage values for the production of liquid hydrogen (LH2) gas using steam reforming of natural gas, where the existing fuel network structure and associated energy flows can be augmented to describe the steam reforming plants for hydrogen fuel processing, compression tank, and fuel transportation elements (Koroneos et al, 2004; Granovskii et al, 2005). As seen in this example, this model's structural and analysis framework can be used to include other transportation modes and energy flows that have not been considered in the scenarios for this thesis.

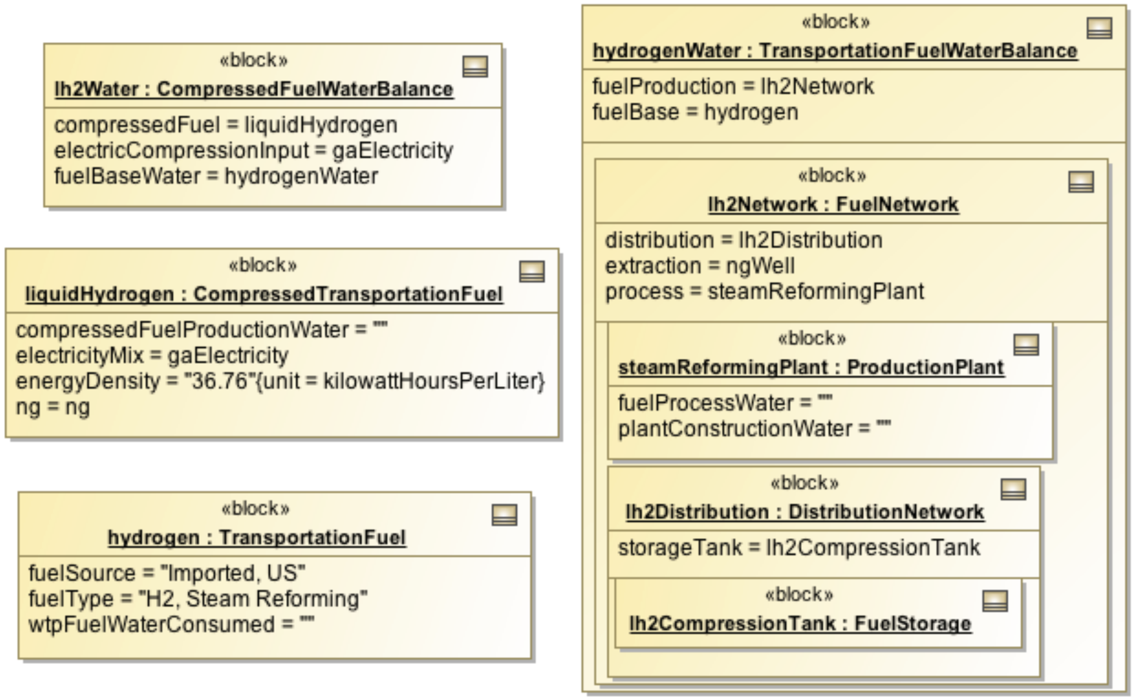


Figure 136. Example of Leveraging Existing Fuel Analyses for Liquid Hydrogen Production Water Consumption.

One of the main sources of motivation for the development of this model as stated in Chapter 2 was whether a decision support framework can be developed to help policymakers and other key stakeholders implement sustainable transportation solutions. While this model assesses water consumption on multiple levels and multiple transportation modes and provides a fairly consistent view on daily water consumption for a given transportation system, the projections given in this model are certainly not the only metrics to be considered when implementing alternative vehicle modes. One of the most important pitfalls to avoid in applying and interpreting life cycle assessments of sustainable transportation is to base decisions solely on one or two metrics or parameters without considering other factors such as fuel pricing and other environmental flows or outputs (Reap et al, 2008; Delucchi, 2004). For example, water consumption for each electricity source considered in this model and case study does not correlate with respective greenhouse gas emissions – in fact, there is generally an inverse relationship between the water consumption values traced to fuel production and plant operation and the greenhouse gas emissions for each plant configuration as shown in **Figure 137** and **Table 65** (Wang, 2010). Similarly, fuel prices do not necessarily correlate with water consumption values for corresponding fuels or energy sources. As such, deciding on implementing sustainable transportation solutions based on water consumption alone would be potentially detrimental to environmental emissions or would not accurately reflect socioeconomic factors for a given region (Delucchi, 2004).

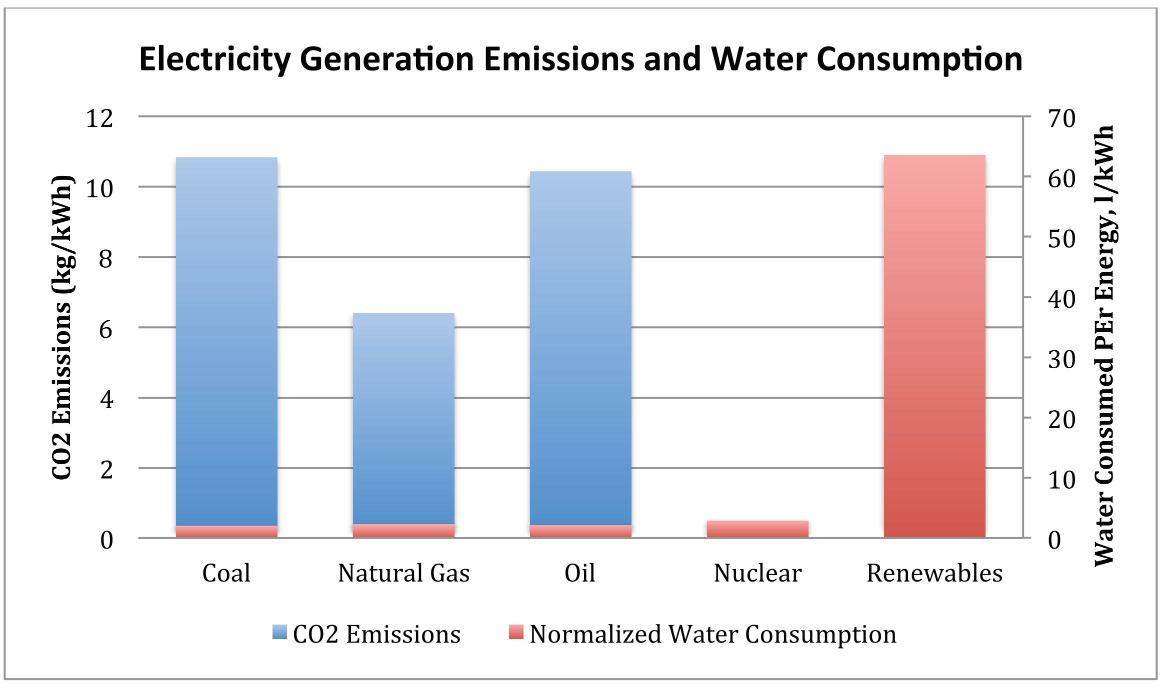


Figure 137. Comparison of Electricity Generation Carbon Dioxide Emissions and Water Consumption.

Table 65. Comparison of Carbon Dioxide Emissions and Water Consumption By Electricity Source.

Electricity Generation Source	Electricity CO_2 Emissions (kg CO_2/kWh)	Normalized Water Consumed, l/kWh
Coal	10.827	2.003
Natural Gas	6.403	2.258
Oil	10.432	2.1198
Nuclear	0.1439	2.873
Renewables	0	63.597

Ultimately, given that this model can be augmented and expanded relatively easily to accommodate other analyses and environmental assessments this framework is potentially valid for other forms of use-phase assessments. While this cannot be completely verified until this model is actually used for other applications, the above potential expansion of analysis components suggests that this model could, at the very least, be used as a template to conduct further investigations on environmental impacts from the usage of transportation modes. As for determining whether the model's results (based on the scenarios in this chapter) are useful for stakeholders and associated policy-making processes, a more comprehensive outlook of water consumption is needed – in other words, adding more public transit modes such as light rail and other vehicle infrastructure components such as mobility hubs, fuel and charging stations, and parking facilities – for conducting a large-scale assessment on all environmental impacts, although for this model intermediate decisions can be made on increasing alternative vehicle shares or altering electricity generation for a given region; even with the omission of some infrastructural elements, this model has shown to be expandable so that modelers and stakeholders can implement and consider these components later on.

CHAPTER 9

CONCLUSIONS

9.1. Final Summary

The previous eight chapters outlined the underlying issue of water usage and stresses on local water resources in addition to the emergence and possible expansion of alternative fuels and energy sources for urban transportation modes, from which several key questions regarding the dependency of transportation network parameters and usage on water consumption as a whole as well as on the possibility of assessing water consumption from local resources for an entire transportation system. Previous assessments and studies on water consumption and usage in the production of electricity and fuels necessary for automobiles and other relevant transportation modes were discussed – from which several input parameters relating to process component water consumption were leveraged for the previous case study and scenarios – along with emerging research and concepts on measuring transportation system parameters as well as with implementing sustainable and resilient mobility networks.

Based on all of this previous research, it was proposed that the network-level assessment of transportation-related water consumption could be evaluated through the implementation of a multi-level, reusable, and object-oriented system model using the Systems Modeling Language (SysML) and MBSE principles. As such, a structural and parametric breakdown was constructed detailing aggregate water consumption for individual transportation modes – in this case, automobiles and public transit buses – as well as for associated infrastructure via a top-down system hierarchy of multiple levels of abstraction.

From there, a water consumption case study was developed using Atlanta's transportation network – in particular, the region's assumed fuel and energy pathways, private automobile fleet broken down by national market shave percentages, assumed MARTA bus fleet distribution, and associated road and vehicle service infrastructure – based on a combination of region-specific network metrics and characteristics along with national averages. In order to assess the reusability of the transportation network model, a series of scenarios alternating between Georgia and Washington State's electricity generation distributions and projected vehicle fleet distributions for 2010 and 2030, along with current and future vehicle efficiency values or plant technology configurations, were assessed using separate instances of the model framework.

Ultimately, it was found that the majority of use-phase water consumption – based on the water consumption breakdown proposed for this model – was either traceable to automobile fleet usage or to service/washing infrastructure for the transportation modes used in this network. In terms of automobile usage, the majority of daily water consumption can be traced to three underlying factors: the vehicle's tank-to-wheel efficiency (represented in this model as fuel or energy efficiency), the amount of water consumed in the production of the vehicle's energy source(s), and the distance traveled by the vehicle within the network for a given day. Based on sensitivity analyses for these variables (as conducted in the final two scenarios), modest improvements and reductions in fuel or water consumption for these vehicles go a long way in reducing individual vehicle type water consumption for gasoline, CNG, and electric vehicles. Similarly, reducing the average daily travel distance for the automobile fleet in this network, as shown in the Seattle electricity and network parameter scenarios, reduces each conventionally powered vehicle's share of daily water consumption. While buses consume significantly more fuel during their use-phase, the low number of buses used in this case study as opposed to the 2.3-3.2 million automobiles in these scenarios results in a much smaller daily water consumption estimate for the network's bus fleet.

Of all of the vehicles being considered, the consistently lowest water consumption for both automobiles and buses are that of CNG-powered vehicles – this is primarily due to the low water consumption values for the extraction, refining, and distribution of natural gas. Gasoline-powered vehicles consume slightly more water during their use-phase when considering only gasoline refining in the production pathway and over twice as much water when considering an additional mix of gasoline recovery processes, while for the Georgia and Washington State electricity mix battery electric vehicles and plug-in hybrid vehicles consume the most water during their usage.

Biofuel-powered vehicles – ethanol and biodiesel – consume the next largest amounts of water of all of the vehicle configurations being considered in nearly all of the scenarios conducted, with the exception of the hypothetical 2030 scenario where a mix of soybean and microalgae-based biodiesel and corn/switchgrass-based ethanol have the two largest water consumption values. In these scenarios, the majority of water consumption in biofuel production and distribution can be traced to evapotranspiration from feedstock irrigation or process water, while production-related water consumption is slightly higher based on estimates from previous research. Improving fuel efficiency in these vehicles (either through more efficient IC powertrains or implementing hybrid powertrain configurations as shown in the 2030 scenarios) drops use-phase water consumption slightly, but more significant improvements can be made in using less water-intensive feedstock as switchgrass or growing bioenergy crops in areas that require less irrigation or have a climate that results in less evaporation. Mixing switchgrass-based ethanol with corn-based ethanol as shown in the hypothetical 2030 scenario results in a noticeable decrease in water consumption, while including alternative feedstock for biodiesel does not necessarily decrease water consumption. Based on these results, increasing usage of biofuel-powered vehicles can add even more stresses to local water resources and disrupt water, land use, and crop allocations for agriculture for other uses, such as for food production; improvements and reductions in water stresses can be made through implementing more drought-resistant crops or using any crop waste or components not allocated to food production or other applications.

While electric vehicles are currently only beginning to be implemented and represent a small fraction of total daily water consumption in 2010, their water-intensive nature will pose potential stresses in local water resources in 2030 as vehicles with EV powertrains – particularly that of PHEVs – become more widespread. However, this water consumption estimate – as with that of vehicle and road infrastructure – is highly dependent on the makeup of the region's electricity mix. In the first four scenarios and in the extraction-included scenario, the largest water consumption component in electricity generation can be directly traced to the evaporative and seepage losses from hydroelectric reservoirs. In both state electricity profiles, the total amount of water evaporated from these reservoirs for one month of electricity generation is quite similar despite the tenfold difference between Washington's average evaporation rate and Georgia's rate; the similarity in aggregate values is due to Washington's majority of electricity coming from hydroelectric sources. In terms of thermoelectric generation, individual plant operation water consumption values for each source – coal-fired, NGCC, oil-fired, nuclear, or biomass-fueled – are comparatively low with respect to hydroelectric generation. These individual water consumption rates are projected to be even lower in 2030 with the inclusion of more efficient plant components such as supercritical boilers for coal-fired power generation and high-temperature gas reactors for nuclear power generation in place of conventional light water reactors. Water consumption from these plants can be improved even further by eschewing water requirements for cooling via implementing dry-cooling configurations or by implementing additional technologies such as coal gasification. Furthermore, the implementation of other renewable sources, such as solar and wind power, can reduce dependencies on local water resources as minimal amounts of water are needed for these sources; however, such sources are only productive in certain regions where sun or wind are readily accessible.

However, as shown in the Georgia and Washington 2030 scenarios, these improvements in thermoelectric power generation are offset by the large water consumption estimates for hydroelectric power; using Atlanta's transportation network, only through the removal of hydroelectric power for electric vehicle or vehicle infrastructure usage can EVs or PHEVs become a sustainable vehicle alternative in the near future.

For road and vehicle infrastructure usage, the majority of water consumption can be traced to water consumed in the production or de-icing materials such as salt as well as to water consumed in vehicle washing (in addition to water indirectly consumed from electricity production). However, these are based on a few assumptions: 1) that the amount of water consumed in producing salt for de-icing is the same in the United States as in Switzerland (from which the data is sourced), 2) that the roads in the transportation network actually need de-icing, and 3) that there is an even distribution of water consumption over 14 days between car washes. Removing salt from the set of material flows for road operation greatly decreases water consumption; similarly, water usage in vehicle washing and maintenance can be reduced through implementing water recycling or increasing washing or servicing intervals. The inputs for vehicle servicing and washing are also questionable in terms of sourcing and scope, and actual electricity and water consumption figures for a given transportation network in the United States may vary greatly, as shown in the sensitivity analysis pertaining to vehicle maintenance.

9.2. Conclusions and Findings

The above results and variations in water consumption shows that allocating and assessing these water consumption factors in a reusable, object-oriented model framework can indeed be done via the implementation of SysML and MBSE principles. Based on definitions of common water consumption and network/component performance metrics and the implementation of generic structural components that can be reused or referenced in multiple instances or configurations, the system model developed in this thesis was shown to be able to be leveraged to several network scenarios and case studies. While the assessment scope for transportation-related water consumption is limited for this thesis and associated model, a few conclusions and remarks can be made from these results.

The first remark is that water consumption for a multi-modal transportation network is heavily dependent on the efficiency of individual transportation modes and infrastructures, the water intensity of energy and material flows, as well as on the spread of the entire network. Reductions in water consumption, for example, can be made in consolidating urban networks and limiting the need to travel great distances between residential and commercial or industrial sectors of a given region. Similarly, water consumption can be reduced in implementing production methods that require little to no water in their operation, such as in replacing current power plants with water cooling configurations with air-cooled systems or non-hydroelectric renewable configurations or in replacing current feedstock or raw materials with those that require little to no water input. Additionally, use-phase water consumption can be minimized further by implementing vehicles that use less fuel or energy, as evidenced with the inclusion of diesel hybrid and gasoline hybrid vehicles in some of the previous set of scenarios.

The second conclusion that can be made based on the literature review (and to a lesser extent, the model and case studies) is that location is also a key factor in determining the viability of alternative transportation modes and energy sources with respect to water consumption. As shown in **Chapter 3**, the majority of water consumption stems from evaporative losses, and as shown in the variations between hydroelectric power water consumption between Georgia and Washington State, such variations become driving factors in assessing whether alternative fuels and transportation modes such as biofuel-powered vehicles and electric vehicles would be sustainable in either region. Based on these variations, it can be said that while electric vehicles and biofuel-powered vehicles would be more attractive in some regions or states may have less water-intensive energy production and more favorable climates that result in less evaporation, these vehicle types would not be suitable for areas that have greater water stresses and higher evaporation rates. Given the significant increases in water consumption from considering mining and crop production for transportation fuels, it should be noted that while some regions may not be favorable for producing or processing fuels or energy sources, other locations may be more viable – for example, ethanol and biodiesel can be imported from other states that have significant water resources to regions that may have more limited water availability.

This leads us to the final conclusion, which states that while water usage is certainly an environmental impact that should be closely examined, such decisions regarding using more alternative fuels and renewable energy sources cannot be made by looking at water requirements alone. Water consumption is not always in agreement with other environmental factors such as output emissions; for example, sticking with conventional fuels for transportation usage in an attempt to minimize water resource stresses for a certain region could ultimately increase emissions and affect climate or temperature patterns, which could lead to increases in evaporative losses and water consumption. Furthermore, water consumption values such as the estimates determined in the previous few chapters need to be consistently benchmarked with overall water consumption for all economic sectors within a given region; while this was not properly implemented in this case study due to that overall water data for Georgia and Washington was based on water consumption *and* withdrawals), it is important to know how much the transportation sector takes up in terms of water consumption and whether a region can sustain increased consumption values in the near future. Ultimately, instead of focusing on a single environmental factor, multiple parameters would need to be considered in order to find a balanced outlook on implementing alternative fuels and transportation modes.

9.3. Answers To Research Questions

Several research questions and hypotheses were posed in Chapter 2 in order to provide a general direction for assessing transportation-related water consumption within an urban mobility network. The following sub-sections present some answers to these questions based on the work and findings documented in this thesis.

9.3.1. Initial Research Questions

The first two questions posed in this thesis dealt with determining the total well-to-wheel water consumption for any given transportation mode and what water consumption factors would be relevant to a transportation mode's given infrastructure. These two sub-questions were addressed in the literature review of energy production water consumption and vehicle usage comparisons in addition to the development of the system model and its associated network scenarios. Well-to-wheel water consumption for any transportation mode, as discussed in this thesis, is a combination of the water consumed in the production of the vehicle's energy source – electricity or liquid/compressed fuels – and how much fuel a vehicle uses over a specified unit distance or time (in terms of vehicle efficiency values); this relationship was implemented using SysML via the model's parametric framework where water consumption from fuel or electricity production is combined with the vehicle's fuel efficiency and driving distance in order to estimate use-phase water consumption for a given day within a specified transportation network.

The second question was only partially addressed as the scope of the infrastructure in this thesis and system model was comparatively small. In this thesis, the primary infrastructure attributed to the transportation network of interest included road networks, vehicle service and washing facilities, and multi-modal transport hubs – in addition to the fuel and energy production and distribution pathways attributed to this transportation network. For road network operation, water consumption factors included water consumed in the production of material flows such as for paint and de-icing materials as well as water consumed in the production of diesel required to operate road network-associated heavy equipment or electricity required to operate electrical components such as signage, surveillance elements, or lighting. Similarly, water consumption factors for vehicle servicing included water consumed in generating electricity for facility inputs or water consumed in periodically washing vehicles. For mobility hubs, it is assumed that the key water consumption factors for their usage and operation would also be traced to water consumed in electricity generation, although analyses pertaining to mobility hub usage were not implemented in this model.

9.3.2. Core Research Question

The core research question presented in **Chapter 2** was the following: Given the water impacts for individual transportation modes and components, what is the water consumption for a multi-modal and multi-level urban transportation or mobility network? This question itself was expanded to include any aspects or metrics pertaining to a mobility or transportation network that may help in answering the above question in addition to determining what methodology would be suitable for this assessment, in which it was hypothesized that aggregate water consumption for any given multi-modal and multi-level urban transportation network can be assessed through the use of a structured system model supported by Model-Based Systems Engineering principles and the Systems Modeling Language (SysML), as they can provide a repeatable, spatially explicit framework for such analyses.

9.3.2.1. Determining Total Network Water Consumption

Based on the work done in determining key water consumption factors in energy production pathways and vehicle usage and in developing this model, it can be said that this question has been partially addressed. With regards to determining water consumption for a multi-modal transportation network, the model and corresponding case study/scenarios only considered road-based transportation modes; given that a mobility network includes other forms of transportation such as air-based transportation or light rail vehicles, a more comprehensive outlook of water consumption within such a transportation system will require the expansion of model components that represent additional transportation modes. Similarly, while some infrastructural components such as road networks and servicing facilities were included in this model and case study, additional infrastructure components such as multi-modal mobility hubs have not been fully implemented in this model. As such, the main question in determining the total water consumption for a given urban mobility network cannot be completely answered with this model and case studies simply because the scope of the model in terms of transportation modes and life cycle phase (the model primarily focuses on use-phase inputs instead of inputs and flows throughout the network's entire life cycle).

9.3.2.2. Relevant Mobility Network Metrics and Indicators

The first sub-question attached to this core research question and hypothesis pertained to determining what aspects and indicators would be relevant to an assessment of network-level water consumption for a mobility network. This sub-question was somewhat addressed in the literature review and model implementation as discussed in this thesis, in which network metrics that would be relevant in this analysis included the average daily distance traveled by a network's transportation modes (the DVKT value implemented in the system model and varied between Atlanta and Seattle in the case study scenarios), travel times or delays, and associated monetary costs pertaining to traffic delays and flows (such as the travel time index discussed in **Section 5.3.1**). More mobility-focused metrics include passenger-miles and passenger capacity for any given transportation mode, while other metrics that were leveraged from previous research and assessments for this analysis included road lane mileage describing the extent of the network's road infrastructure. These parameters were added to the set of vehicle performance metrics (vehicle efficiency and market share percentages, for example) in the system model.

However, while several parameters were found to be relevant to assessing network-wide transportation network water consumption, not every parameter was used in this version of the system model and case study. For example, this model assesses water consumption based on vehicle-miles/vehicle-kilometers traveled based on vehicle efficiencies and daily travel distances but does not use passenger capacity or mobility-related metrics such as the number passenger vehicle-miles. Similarly, other transportation metrics such as parameters pertaining to congestion and traffic delays were ultimately not included in the model. As highlighted in the validation for this model, however, additional parameters and parametric layouts/analyses can be added as needed, and the implementation of such metrics that were overlooked in this version of the system model could ultimately be attached to the model's structural or analytical hierarchy later on.

9.3.2.3. Assessing Water Consumption On Multiple Levels Of Detail

The next question that branches from the core research question in this thesis focused on how to assess multiple levels and scales of water impacts for a given mobility network without losing too much detail in addition to how these elements can be traced. It was hypothesized that, based on previous research in assessing and modeling sustainable systems, SysML and MBSE principles can be applied to develop a traceable and reusable model that can break down water consumption in multiple levels and allow for the monitoring of intermediate and top-level water consumption estimates.

The development and implementation of this model as suggested in **Chapters 5-8** show that this hypothesis can be confirmed, in which the object-oriented modeling framework in SysML allows for a multi-level definition of transportation system domains and individual network components in addition to clearly-defined water consumption values and performance metrics for each level. Top-level water consumption values and network-level metrics can be defined just as clearly as individual vehicle efficiency values and process-level water consumption values within the model thanks to the definition of concrete value properties within the structural and analytical elements in SysML. The implementation of intermediate water consumption values – in this case, the ancillary values defined within a specific domain or vehicle mode and linked with individual water consumption components in the model's parametric framework, can be tracked and analyzed effectively using ParaMagic and other analysis tools. Furthermore, the traceability and reusability of elements within this model can also be traced to the definition of individual or domain-level analyses through the entire model, which allows for a clearer allocation of input and output values for each level of the mobility network representation in SysML.

The implementation of MBSE process elements within the SysML implementation process enhances the traceability and clarity of multiple levels of abstraction in this model. Each set of structural and analytical components in this model can also be easily allocated to concrete analysis or modeling requirements for traceability, and further relationships can be clearly defined through the representation of physical interactions and flows between individual network components and domains. Similarly, function structures undertaken by specific network components, such as that of fuel or energy production pathways can be defined using SysML in order to provide a clearer outlook of indirect or direct water, material, or energy flows within these pathways and networks.

However, this implementation is not without shortcomings and issues. While ParaMagic in its current version (16.8 as of this thesis) is more stable compared to previous applications of SysML models, this analysis execution tool requires modelers to make additional changes in order to ensure that the analyses could actually be done, such as in adding intermediate values for every step in each parametric breakdown and in implementing constraint blocks that need to be compatible with Mathematica or any other associated external analysis tools. As pointed out in previous applications of SysML and ParaMagic, these additional changes increased the amount of time in setting up analyses and implementing workarounds and potentially offset any improvements from streamlining model or system development through reusable objects and intermediate requirements tracking. Furthermore, any further analyses of water consumption with respect to other environmental or economic factors such as pricing or output emissions – particularly with those of multi-objective optimization – are possible with other analysis tools but not currently with ParaMagic; as such, while separate analyses can be conducted for individual parameter types, there isn't necessarily any room for optimization.

Another issue for SysML and ParaMagic being applied to this analysis and model framework pertains to linking this model to existing assessments or life cycle models. Currently, the population of input parameters for each scenario and set of instance specifications is done by linking individual slots to corresponding cells in Excel spreadsheets that contain relevant values; however, these values were manually entered from existing models and datasets, and implementing vastly different data sets or values for completely different case studies would require excessive time and effort through such manual input.

That said, for the purposes of the scope and definition of this thesis, this hypothesis can be somewhat confirmed based on the model developed and implemented within SysML. While the scope of MBSE principles and process components is limited to requirements tracing and functional or analytical decompositions of system elements, the application of object-oriented modeling and the above MBSE components in SysML for this model has allowed for a reusable and traceable model framework that can, with some additional effort and revisions, be utilized for multiple scenarios and analyses using ParaMagic. Despite some small issues pertaining to the implementation of ParaMagic, stability improvements and a primary focus on use-phase water consumption in this analysis and model makes ParaMagic ultimately useful for this application.

9.4. Shortcomings and Future Work

One major component of a mobility network left out in this model is the element of vehicle occupancy and passenger capacity for the transportation modes being considered. Currently, network-level water consumption is based mainly on individual vehicle types and associated infrastructure and not on individual passengers using these vehicles; the primary reason for this lack of implementation is that the implementation of passenger capacity (and subsequently the passenger-vehicle kilometers traveled (PVKT) metric) would limit the scope of the analysis solely to vehicle usage in terms of bus and automobile operation. However, just because this model does not account for passenger occupancy does not mean that it is not a vital parameter to consider in a transportation or mobility network – in fact, as described in Litman (2003), the passenger-distance unit represents a key metric of mobility performance for a given region. Furthermore, the inclusion of passenger occupancy into this model framework expands the model to include more transportation modes such as light rail vehicles and other configurations that can facilitate water consumption calculations on a per-passenger basis. For existing transportation modes, considering passenger occupancy could shed some light on mobility performance for the automobile and bus fleets in this network – for example, further case studies could be implemented that would explore increasing vehicle occupancy while lowering the number of vehicles in a given network.

One other major shortcoming in this model is the turnaround time for assigning input variables for a given scenario and interpreting multi-level results and output variables. This is especially apparent in the specification of individual water consumption values for fuel and energy pathways in this model, where a large amount of input data needs to be properly organized and inputted for calculating normalized water consumption averages for a given electricity mix and well-to-wheel water consumption for vehicle modes and associated transportation fuels. Similarly, numerous input parameters such as vehicle market share, driving distance, and vehicle efficiencies are required for a network-level analysis, along with individual material consumption inputs for a given road infrastructure. While the Excel-ParaMagic integration has been improved from previous versions and allows for linking individual values in each instance to defined Excel spreadsheet cells, any changes in the Excel spreadsheet's organization (or in the spreadsheet's filename and location) require the modeler to re-link individual values, which in some cases may involve individually re-linking variables from scratch.

Another area for potential future work is to expand the model's structural and analytical framework to assess other environmental or economic flows for a given transportation system. For example, the water consumption for each vehicle mode is potentially inversely proportional to each mode's carbon dioxide emissions, and the potential implementation of alternative vehicle modes needs to consider economic conditions and other factors such as fuel pricing and availability. Ideally, in determining a favorable vehicle distribution for a given transportation network, a multiple-analysis framework using this model can also leverage existing optimization methods to minimize emissions, water consumption, and fuel/energy costs; however, an analysis tool that supports such optimization of these parameters would need to be implemented.

APPENDIX A

ADDITIONAL CALCULATIONS & MODEL COMPONENTS

A.1. Supporting Calculations

The key parametric expressions for this water consumption model and associated analysis were described in **Section 5.3**; however, given the vast amount f constraints implemented in this model, only top-level constraints detailing total water consumption for a given fleet of transportation modes or for a given infrastructural domain were described in that section. The following sections will detail lower-level calculations describing water consumption for individual energy pathways, material and energy flows, infrastructural components, and individual vehicle modes.

A.1.1. Vehicle Type Well-To-Wheel Water Consumption

The well-to-wheel water consumption is directly related to the well-to-pump water consumption for each vehicle's associated fuel or energy source, as well as the vehicle's pump-to-wheel efficiency (in the form of fuel efficiency for gasoline and biodiesel vehicles or energy efficiency for electric vehicles). Based on that, the well-to-wheel water consumption for petroleum gasoline and biofuels can be expressed as the following in **Equations 7 and 8**, where the fuel efficiency of each vehicle is described as **FE** (in terms of L/km); for electric vehicles, the well-to-wheel electric vehicle water consumption combines the well-to-pump electricity generation water component with the vehicle's energy efficiency **EE** (in terms of kWh/km, or energy consumed per kilometer) and tank-to-wheel efficiencies η_{EV} that are the product of battery charge/discharge, motor, and drivetrain efficiencies (Harto et al, 2010; King and Webber, 2008 (1); Campanari et al, 2010).

$$W_{WTW-use}\ [l/km] = W_{WTP} * FE \tag{7}$$

$$W_{WTW-use}\ (EV)\ [l/km] = \frac{W_{WTP-e} * EE}{\eta_{EV}} \tag{8}$$

$$\eta_{EV} = \eta_{charge} * \eta_{discharge} * \eta_{motor} * \eta_{drivetrain}$$

A.1.1.1. Auxiliary Fluid Water Consumption Calculations

Additionally, there is some process water consumption related to each vehicle's auxiliary fluids; for this mathematical model, the fluids to be considered will be that of coolant mixtures for IC-engine vehicles and battery-electric vehicles as well as that of the engine lubricants for IC-engine vehicles. For this model, it is assumed that the amount of each fluid stored in all passenger automobiles is the same; scaled-up estimates are used for public transit vehicles. For engine lubricants, primarily that of motor oil, it is assumed that such lubricants are based primarily on petroleum-based materials; as such, the well-to-tank water consumption intensity for petroleum (to be discussed in the next subsection) is used. For IC vehicles, the engine coolant is composed primarily of water and ethylene glycol (antifreeze), for this model, fluid volumes from Ford that correspond to the addition of these fluids during final assembly are used – it is assumed that the coolant composition is half water and half antifreeze for either IC and electric vehicles (Zullo and Ford, 2010; Nissan, 2011). To estimate the water consumed in the production of engine or battery coolants, the water consumption intensity for ethylene glycol production is used – either as itself or in addition to water added to the coolant mixture (Althaus et al, 2007). For each of these fluids, it is assumed that engine lubricants are replaced after a specified traveled distance and that coolants are intermittently added across a vehicle's service life; as such, in order to match the use-phase water consumption (in liters per kilometer), the water consumption for each fluid is divided by its assumed service interval *SI* (in terms of kilometers), as shown in **Equation 9**.

$$W_{fluid}\ [l/km] = \frac{W_{WTP,petroleum} * V_{lubricant}}{SI_{lubricant}} + \left[\frac{\left(W_{WTP,antifreeze} * V_{antifreeze}\right) + V_{water}}{SI_{coolant}}\right] \tag{9}$$

A.1.2. Well-To-Pump Water Consumption For Transportation Fuels

As explained in **Section 5.1**, direct well-to-pump water consumption for transportation fuels such as that of petroleum gasoline/diesel and biofuels can classified into three major components – water consumed during fuel or material extraction, water consumed during the processing and production of these fuels, and water consumed in the distribution and storage of these fuels. In many of the previously developed life cycle models and assessments, these values are accumulated and a total water consumption value for each of these fuels is determined based on a specified factor depending on the amount of produced fuel that is solely dedicated to transportation fuels (Wu et al, 2009; Harto et al, 2010); for this model, it is assumed that all of the produced fuel is allocated to transportation or energy purposes as there is no consistent data on how much fuel is allocated for each sector by region. Additionally, for fuels that may be viable for a regional transportation system but may not have any existing infrastructure (such as that of biofuels), there is an additional water consumption variable pertaining to water inputs for constructing the necessary production plants and distribution systems for these fuels (Harto et al, 2010). As such, the well-to-pump water consumption for petroleum-based fuels and biofuels is the sum of all four water consumption components as shown in **Equation 10**, where $W_{infrastructure}$ pertains to the amount of water consumed in upfront facilities construction; these values are in terms of liters of water consumed per liter of produced fuel.

$$W_{WTP} = W_{extraction} + W_{process} + W_{distribution} + W_{infrastructure} \tag{10}$$

However, the above expression only pertains to transportation fuels that do not need any additional material or energy inputs while they are being stored – on the other hand, fuels such as compressed natural gas and liquefied petroleum or natural gas require additional inputs in order to make those fuels usable for transportation purposes. The compressed fuel to be considered in this model, compressed natural gas (CNG), requires on-site compression at storage and fueling facilities in order to be pumped into CNG-powered vehicles; to do this, natural gas is compressed in cylindrical storage tanks either by injecting additional gas in order to increase the tank pressure or by using electrical compressors (Wang and Huang, 1999; King and Webber, 2008 (1)). Based on these observations, a storage-related water consumption variable is added to the well-to-pump water consumption for compressed natural gas based on a required pressure of 4000 psi and associated electricity inputs, along with a natural gas compressor rated at 91.7% where 8.3% of the gas is used to operate the compressor (King and Webber, 2008 (1)). In this model, it is assumed that gas compression is evenly split between electricity-operated compressors and gas-operated compressors. The associated water consumption balance for CNG storage compression is shown in **Equation 11,** where $r_{compression}$ denotes the gas compression ratio, $\eta_{gasCompressor}$ the gas compressor efficiency, W_{WTP} the well-to-pump water consumption for producing uncompressed natural gas, $W_{electricity}$ the well-to-pump normalized water consumption for electricity produced within the regional electric grid, and $e_{compression}$ the amount of electricity required for a unit volume of compressed fuel (in kWh/liter).

$$W_{compression} = \frac{(\eta_{gasCompressor} * r_{compression} * W_{WTP}) + (e_{compression} * W_{electricity})}{2} \quad (11)$$

A.1.3. Well-To-Pump Water Consumption For Electricity Generation

In allocating water consumption for electricity generation, we encounter a very similar expression formulation for the total normalized water consumption. Given an energy output for a given fuel and associated electricity generation method and the total energy output, along with the water consumption incurred for each generation type, the "well-to-pump" normalized water consumption $\mathbf{W_{wtp\text{-}e}}$ for a given electric grid is shown in **Equation 12**. This weighted average was used in this model in order to minimize uncertainties regarding peak and off-peak power consumption and fluctuations in monthly electricity generation; furthermore, energy outputs for individual energy sources and that of the overall serviced region are based on annual output statistics from the Environmental Protection Agency's eGRID model (Environmental Protection Agency, 2010). An additional parameter added to the water consumption expression is the transmission efficiency, which is needed in order to account for energy losses resulting from electricity transmission via power lines and substations within a local or regional electric grid. For simplification purposes, the transmission efficiency η_{trans} is set to 0.92, which is the national average as observed by the Department of Energy.

$$W_{WTP-e}\ [\,l/kWh] = \frac{\sum_{i=1}^{m} W_{source} * E_{source}}{E_{total} * \eta_{transmission}} \quad (12)$$

A.1.3.1. Water Consumption for Individual Energy Sources – Thermoelectric Generation

Just as with the network distribution of vehicle types, each "type" – in this case, electricity generation source – has its own associated water consumption component. These electricity generation components are broken down based on the structural hierarchy for electricity generation presented in **Section 5.1**, where electricity generation is broken down into thermoelectric power generation and renewable power generation.

For thermoelectric electricity generation, water consumption can be primarily traced to two major components: the production of the fuels required for electricity generation, and the water required for power plant operation for each fuel. Keeping with the same convention as with the well-to-pump water consumption of transportation fuels, the fuel-related water consumption can be further broken down into water consumed in the extraction and mining of the raw fuels, water required to process or refine these fuels, and water consumed in transporting them to their respective power plants for combustion. As previously discussed, extraction water consumption stems from water required for dust suppression or for recovery processes in coal or uranium mining and natural gas exploration or extraction; for fuel processing, this may entail uranium enrichment, coal beneficiation, or natural gas refining.

Based on the above breakdown of water consumption, the thermoelectric fuel-related water consumption can be estimated as in **Equation 13.**

$$W_{WTP,fuel}\ [l/kWh] = W_{extraction} + W_{process} + W_{distribution} \qquad (13)$$

As described in previous life cycle assessments on energy consumption and in the water consumption breakdown for electricity generation, power plant water consumption can be traced to water required for cooling towers and ponds, as well as water needed for emissions scrubbing and other facility-related uses. Ultimately, all of these water consumption components are allocated into an aggregate value $\mathbf{W_{plant}}$, which can be combined with the fuel-related water consumption to obtain the total electricity generation water consumption for each thermoelectric source as shown in **Equation 14.**

$$W_{source}\ [l/kWh] = W_{WTP,fuel} + W_{plant} \tag{14}$$

A.1.3.2. Water Consumption for Individual Energy Sources – Renewable Generation

For the renewable sources considered in this transportation network – hydroelectric, photovoltaic solar, and wind power – there is no water associated with the procurement of fuels needed for power generation, as for hydroelectric power the primary fuel is water (the Department of Energy does not consider the direct water flow from hydroelectric reservoirs to be consumed) and for photovoltaic solar power the primary fuel is sunlight. For wind power, the only water consumption component estimated stems from the construction of wind turbines and other supporting infrastructure (Harto et al, 2010).

That said, there is still a water consumption component(s) for both of these renewable electricity sources. Although the reservoir-based water flow for hydroelectric dams are not considered to be consumed, there is a sizable amount of reservoir water losses resulting from evaporative losses, due to the fact that hydroelectric dams replace flowing-water ecosystems with standing-water conditions, which can ultimately lead to evaporation and seepage within reservoirs (Gleick, 1994). Additionally, there is some amount of direct water consumption pertaining to the operation and maintenance of photovoltaic solar plants as water is consumed mainly in washing and cleaning solar panels – while there are additional water inputs for the manufacture of solar cells and panels for photovoltaic plants, this model is more concerned with the use-phase of these panels (Harto et al, 2010).

Based on the above breakdown of water consumption for hydroelectric power and solar power generation, the water consumption for renewable electricity generation can be expressed as shown below.

$$W_{hydroelectric}[\, l/kWh] = W_{plant}\ (evaporative\ losses) \tag{15}$$

$$W_{source}(PV, Wind)[\, l/kWh] = W_{plant}\ (operation) \tag{16}$$

All of the above thermoelectric and renewable energy water consumption components can then be added to the normalized water balance shown in **Equation 3**.

A.1.4. Water Consumption For Road and Vehicle Infrastructure Material and Energy Flows

The water consumption for producing the raw materials required for road resurfacing is based on the amount of water documented in Spielmann et al (2007) for asphalt, gravel, and paint. Some of these material inputs are produced from a combination of two or more resources, from which water consumption required for procuring these raw materials can be combined. For example, the road paint required for lane and signage marking – as defined in Spielmann et al (2009) – is divided into water-based and solvent-based alkyd paints; based on the process water consumed for each of these paint types, an estimate of per-distance paint-related water consumption can be determined. Similarly, process water consumption for salt required for de-icing can determined for each kilometer of road lane distance based on the amount of salt used.

As such, the total material input water consumption for each kilometer of road can be expressed in **Equation 17,** where the water intensity for each material (in liters per kilogram) is multiplied with the amount of material required per lane. It should be noted that the life cycle data presented in Spielmann et al (2007) and the corresponding Ecoinvent life cycle database are on an annual basis; these components would need to be converted to that of daily water consumption.

$$\sum_{i=1}^{n}\left(W_{roadMaterial,i}\right)\ [l/km] = +(W_{sald} * m_{salt}) + \left(W_{paint} * m_{paint}\right) \tag{17}$$

Similarly, the road material life cycle inputs for road operation and maintenance are coupled with energy inputs including electricity required for each kilometer of road per year along with diesel required for any maintenance or operational equipment required to resurface or de-ice roads. For these life cycle reports, it is assumed that all of the electricity for road-based infrastructure is sourced from the local electrical grid; independent electricity generation sources such as dedicated wine turbines or solar panels for road signage and lighting are not considered in these values. The annual electricity (in terms of kWh) and fuel requirements per kilometer of road are multiplied with their associated water consumption inputs in order to determine the annual water consumption (in liters per kilometer per year) required to produce energy inputs for the road infrastructure of interest (**Equation 18**).

$$\begin{gathered} W_{roadEquipmentFuel}\ [l/km], = \left(W_{WTP}(diesel) * V_{fuel}\right), \\ W_{roadElectricity}[l/km] = W_{WTP-e} * E_{consumed} \end{gathered} \tag{18}$$

For vehicle infrastructure such as service and washing facilities, water consumption is traced to energy and direct water inputs. Service facility water consumption (per year and for each vehicle) can be estimated by adding the annual amount of direct process water and the product of the amount of electricity consumed and the normalized water consumption for said electricity production**,** as shown in **Equation 19**. As with water consumption for vehicle fluids, the water consumption for vehicle servicing is assumed to be the same across all vehicle types for either automobiles or buses.

$$V_{service}\ [l/day] = E_{service,consumed} * W_{WTP-e} \tag{19}$$

On the other hand, water consumption figures provided by Brown (2002) pertaining to vehicle washing is in terms of water used per wash. In order to normalize such data to daily figures, it is assumed that a vehicle is washed every two weeks or 14 days. As there is no distinguishing between automobile washing and bus washing, it is assumed that the low-range water usage value is used for automobiles and the high-range water usage is attributed to buses in order to account for size ranges.

As these two components are assumed to be uniform across all automobiles and for all buses (with separate values for each category), these are added onto the total daily use-phase water consumption for all vehicles of each size within an urban mobility network.

A.2. Additional SysML Model Diagrams and Components: Requirements

Top-level structural and parametric diagrams as shown in SysML, along with any preceding system requirements, were detailed in **Section 5.4**. However, the system model for this thesis consists of far more than just these diagrams and analysis contexts. The following sections detail additional applications of MBSE and SysML in determining lower-level modeling and analysis requirements for specific domains and components, modeling of functions and physical interactions between certain domains and elements within this transportation network representation, as well as more detailed diagrams pertaining to network-level and domain-level parametric layouts that are necessary for determining overall network water consumption.

A.2.1. System Requirements in Tabular Form

Table 66. System-Level Requirements Table.

ID	Name	Text
1	System Model Requirement	Develop a system model of a multi-modal transportation network that supports model reuse and information capture with the intention of mapping water flows and determining transportation-related water consumption for several conventional and alternative vehicle types and supporting road infrastructure.
1.1	Fuel Pathway Requirement	Implement subdomains for fuel production pathways pertaining to the extraction, refinement, and distribution of conventional and alternative fuels.
1.1.1	Fuel Water Consumption Constraint	Fuel water consumption shall be limited to production processes falling under the extraction of raw fuel materials, processing and production of applicable fuels, and distribution of these fuels.
1.1.2	Fuel Pathway Scope	Fuel pathway water consumption shall be restricted to components that affect local water resources. Out-of-state production will not be considered.
1.2	System Scope	The system model shall account for several types of passenger vehicles and public transit road vehicles as well as supporting maintenance and operation infrastructure and supporting road network.
1.2.1	Vehicle Type Scope	The vehicles to be considered shall only include gasoline, biodiesel, ethanol, natural gas, battery electric, hybrid electric, and grid-connected PHEV passenger vehicles and buses.
1.2.2	Vehicle Flows Requirement	The water consumption system model should account for water consumed in the production of a vehicle's fuels and auxiliary fluids (hydraulic fluids, lubricants, coolant).
1.2.3	Vehicle Operation and Maintenance	The system model shall incorporate water flows for periodic servicing and maintenance of the vehicle as well as any water directly inputted into normal vehicle operation or cleaning.

Table 66 Continued. System-Level Requirements Table.

ID	Name	Text
1.3	Electricity Generation Requirement	Develop a reusable, traceable, and general sub-model for describing a regional electricity generation distribution.
1.3.1	Electricity Generation Scope	The model must account for conventional and renewable energy sources as well as associated thermoelectric and renewable power plants and grid infrastructure (ex: power distribution network).
1.3.2	Electricity Generation Water Consumption Scope	Water consumption components for electricity generation (not including fuels) shall only consist of water required for cooling or boiling in thermoelectric plants and water required for operation or cleaning in renewable plants.
1.4	Road Network Requirement	Implement a subdomain for road networks within the transportation network pertaining to road infrastructure for a given urban region.
1.4.1	Road Network Constraint	The system model shall only consider roads falling under class 1 roads, streets, and highways. Interstates and highways are grouped together in this model.
1.5	Water Usage Constraint	The system model shall only account for water consumption (not withdrawal) within local water resources.
1.6	Infrastructural Scope	The system model shall be developed with the assumption that upfront infrastructural water consumption is out of scope, with the exception of water required for normal operation.

A.2.2. Electricity Network Representation Requirements

From the above top-level model requirements, a series of requirements for specifying the electricity generation pathway for the transportation network can be defined. The top-level scope requirement for network-specific electricity generation was refined into a set of requirements dictating the selected generation methods and associated fuels, technology constraints, and component-level assumptions to be implemented in this model. This breakdown of electricity-specific requirements is shown in **Figure 138.**

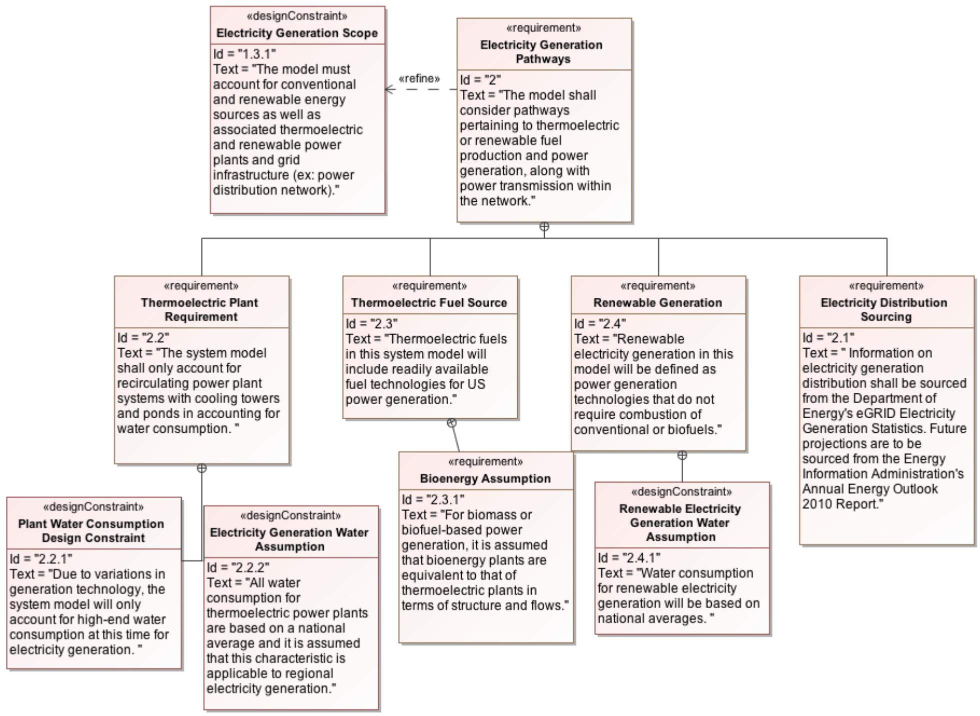


Figure 138. Electricity Model Requirements Defined in SysML.

The electricity generation pathway requirement's sub-requirements pertain to thermoelectric fuel and power generation assumptions and scope, where the requirements are constructed in order to account for the life cycle water consumption data; for example, as power plant-related water consumption is presented in aggregate values for each configuration without any further breakdown, the parameters in the model will only apply to the top-level power plant structure. Another requirement specified pertains to where the electricity generation distribution would be sourced from, which in this case would be based on the EPA's eGRID statistics and on Annual Energy Outlook state data.

Other requirements within this group include specifying the fuels and technologies to be considered for electricity generation. For example, one requirement states that only (currently) economically viable fuels such as soybean-based biodiesel and corn ethanol would be considered in the scenarios for this model, although hypothetical scenarios for future transportation projections could include experimental fuels such as algae-based biofuels or switchgrass ethanol. Similarly, another requirement specifies that only readily available thermoelectric technologies will be assessed for regional scenarios, although the object-oriented nature of the model itself would allow for specifying prototype technologies for other case studies.

A.2.3. Fuel Network Representation Requirements

As with the requirements for electricity generation, the top-level fuel pathway requirements can be further refined to specify the scope and implementation of transportation fuel pathways and associated water consumption inputs in this model, as shown below in **Figure 139**. Sub-requirements for the top-level fuel pathway requirement focus on scoping water consumption assessments to water consumed in extraction, processing, and distribution based on the presented information and typical production processes described in **Chapter 3**; requirements specified include limiting the water consumption to be considered to that of components that use local water resources; for example, extraction-related water consumption for imported coal or crude oil would be outside of the model's scope. Furthermore, other sub-requirements specify the technologies and production/extraction methods to be considered, just as with the requirements specified for electricity generation.

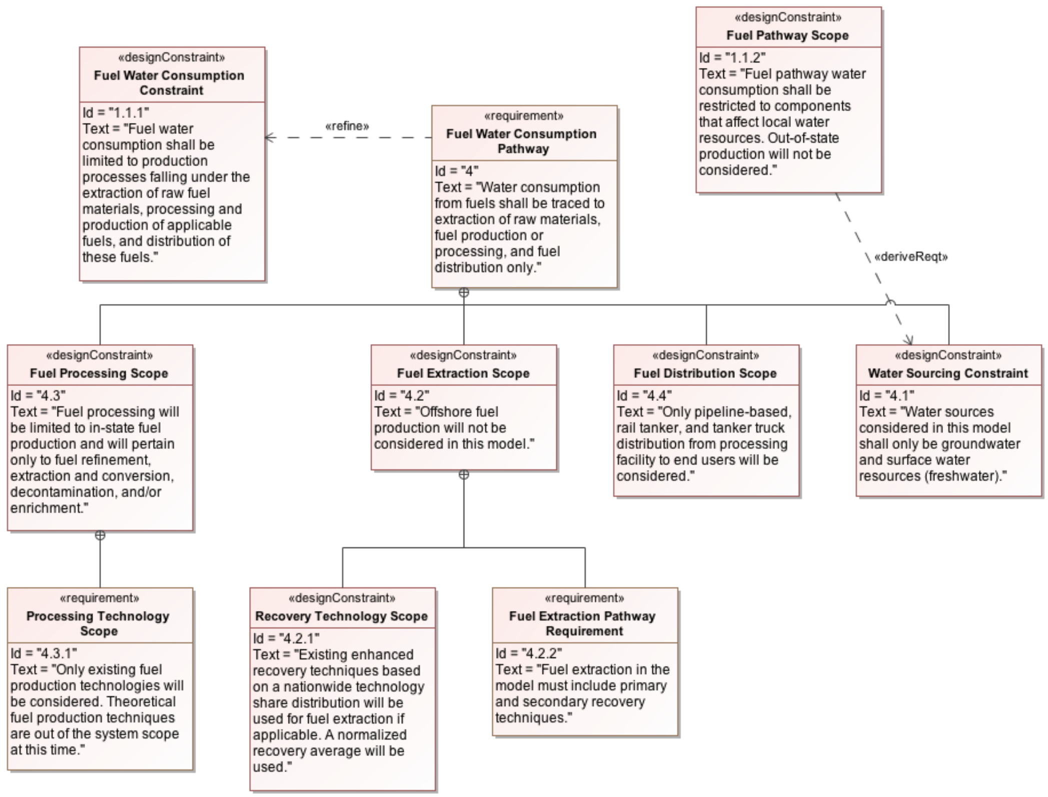


Figure 139. Transportation Fuel Pathway Requirements for the SysML Model.

A.2.4. Vehicle Modeling Requirements

Similarly, requirements pertaining to modeling and specifying the transportation modes to be considered in this network can be defined based on the top-level requirements previously developed. From the outset, the focus of this assessment has been on road vehicles and supporting infrastructure; this is the premise of the **Vehicle Type Scope**, which constrains the model to passenger vehicles and buses based on conventional and alternative configurations such as gasoline/diesel, biodiesel, ethanol, natural gas, and electric/hybrid types. Additionally, these requirements are built from the top-level specification that the model account for use-phase material and energy flows and associated water consumption along with those of the vehicles' service infrastructure. Many of the assumptions presented in the water consumption breakdown, such as simplifications regarding the amount of lubricant and coolant for each vehicle type and the utilization of GREET fuel economy values, are also packaged as requirements and design constraints – as are assumptions regarding vehicle capacity and vehicle servicing (in that direct and indirect water consumption for service flows are the same for each transportation mode). These requirements are summarized below in **Figure 140**.

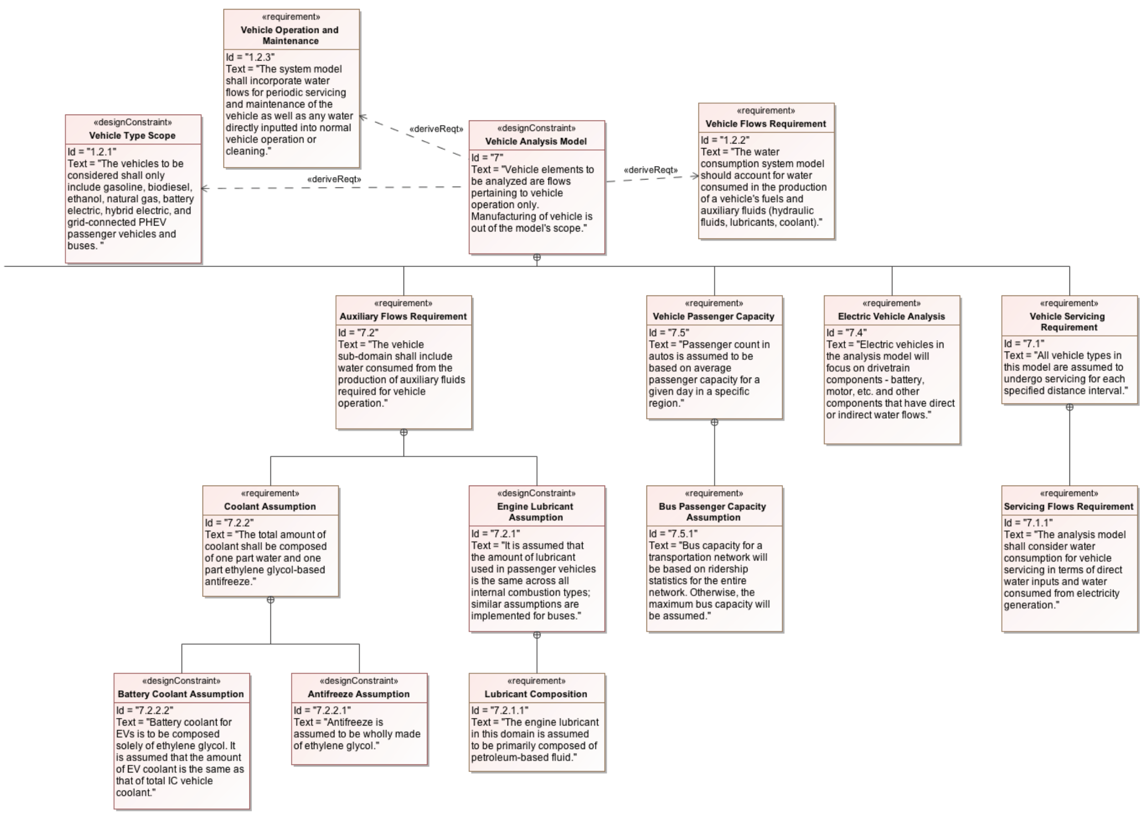


Figure 140. Vehicle Modeling Requirements as Shown in SysML.

A.2.5. Infrastructure Modeling Requirements

The next set of requirements to be derived and specified from the top-level system requirements contains specifications and constraints pertaining to modeling and assessing the infrastructure considered in this model. As the model is oriented towards road transportation modes, the requirements limit the scope of the infrastructure of this model to that of roads and maintenance infrastructure, in addition to the fuel and energy pathways previously specified. Just as with the modeling of vehicles and energy/fuel networks in this model, these requirements are used to scope the extent of the analysis model. Based on the top-level specifications that focus the model on the use-phase of network components in terms of operation and maintenance, the infrastructural requirements extend these definitions in specifying the types of material and energy flows to be considered, road classifications to be assessed, as well as on what operations are to be considered. All of these requirements pertaining to the road infrastructure – the energy and fuel infrastructures are specified within the fuel and energy network requirements – as well as their allocations with top-level requirements are shown in **Figure 141**.

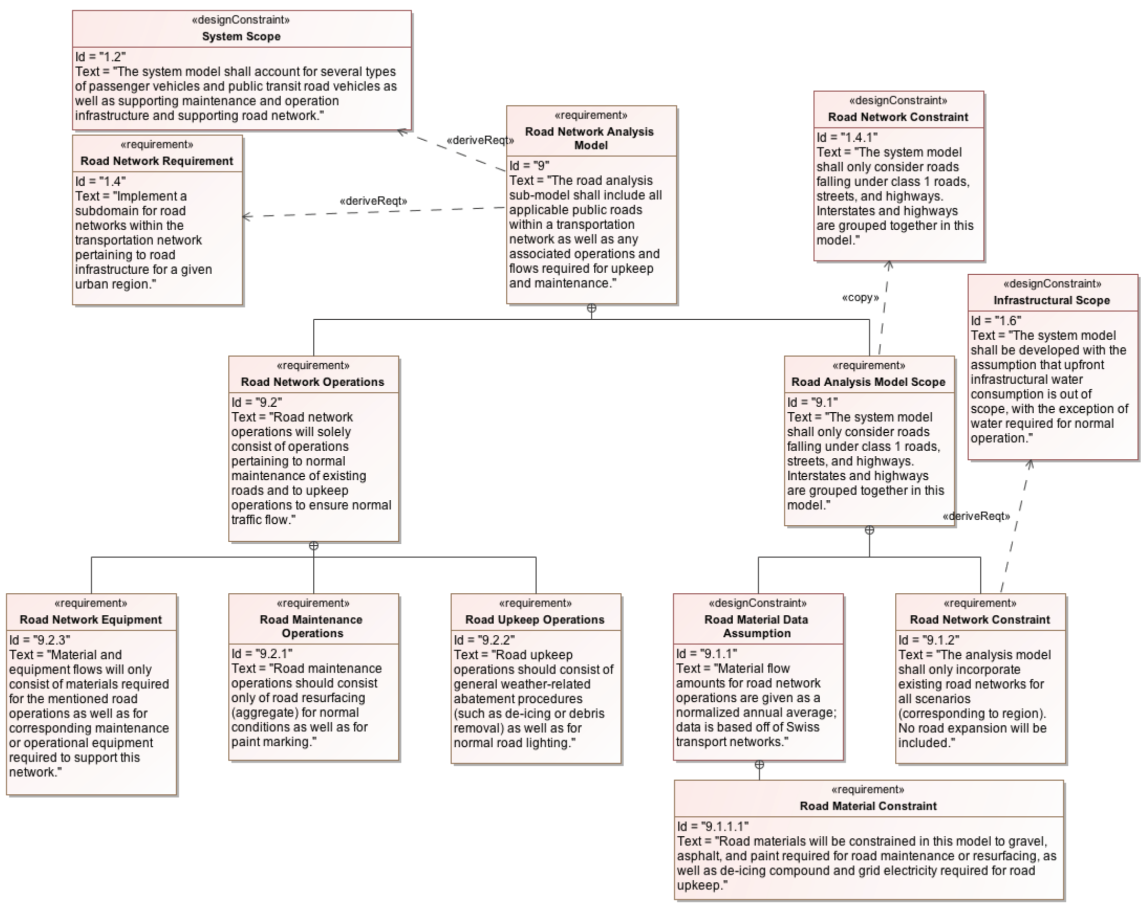


Figure 141. Road Infrastructure Modeling Requirements Breakdown.

A.3. Additional SysML Model Diagrams and Components: Flow Definitions and Physical Interactions

A.3.1. Network Flows

All of the material and energy flows used in this model can be summarized in the following diagram in **Figure 142**, where each flow is a specialization of the generic model element **NetworkFlow**. Flows in this model are divided into material flows for infrastructure and energy production, material flows pertaining to liquids or fluids used throughout the network, and energy sources (in terms of fuel or electricity). Furthermore, some of the primary flows specified on the domain-level breakdown can be further reused or leveraged for specific applications. For example, the generic **Fluid** block (which has a composite association with the top-level **NetworkFlows** block) has a stored value property representing the material's water intensity (essentially the amount of water consumed per corresponding volume of liquid) – by itself, this block is not descriptive enough to represent material flows within transportation modes or infrastructure. Thus, a *specialization* link is added to the Fluid block to more specific elements such as water or petroleum, where the generic block's properties and other associated references be *inherited* to these blocks such that these blocks share the same water intensity value property. The same can be said for raw materials; the **RawMaterial** block is not necessarily useful in describing material flows for different infrastructure types, so more specific representations of materials pertaining to road or fuel infrastructures inherit overall elements stored in the RawMaterial block.

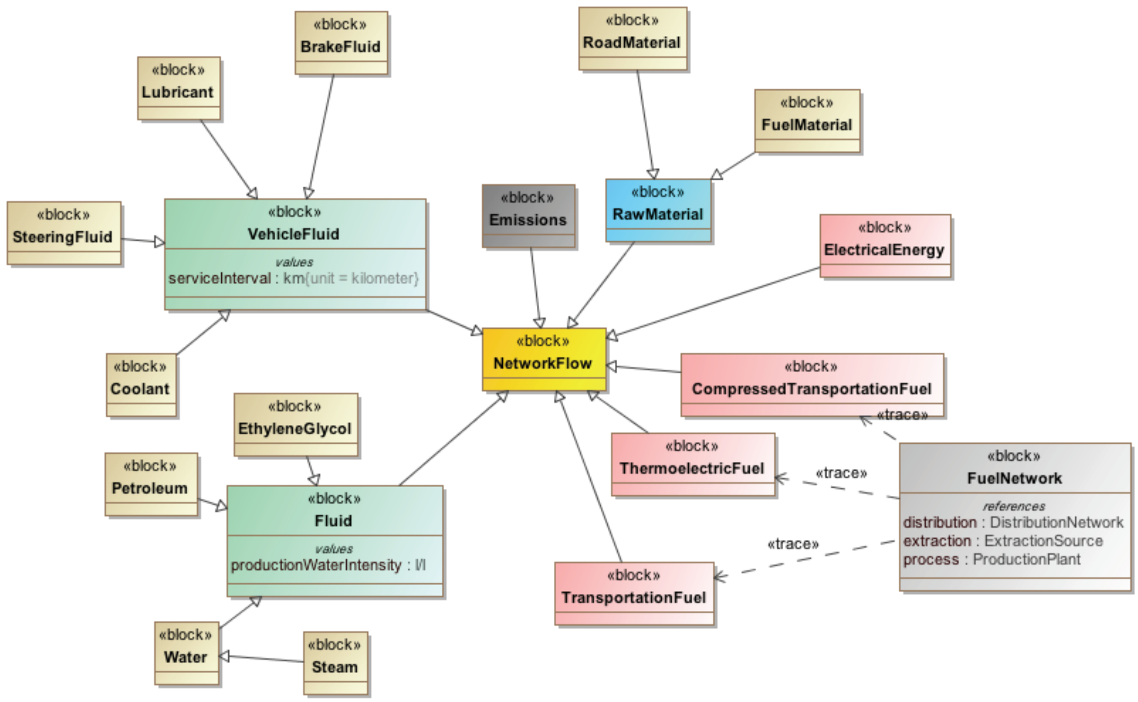


Figure 142. Network Flows Overview.

A.3.1.1. Energy Flows Definition

Each vehicle type and relevant network infrastructure that contains energy flows references an energy source flow defined in this model as four types of energy sources: **TransportationFuel, CompressedTransportationFuel**, **ThermoelectricFuel,** and **ElectricalEnergy (Figure 143**). While individual water consumption components pertaining to fuel extraction, processing, and distribution are attributed to corresponding physical elements represented within the FuelNetwork sub-domain, the calculated normalized or total water consumption values are stored as value properties in these energy source blocks. Other relevant parameters such as the high heating value (HHV) of fuels as well as descriptions of fuel and sourcing are also stored in these blocks, and all of these parameters would be utilized in the analysis portion of this model. Additionally, as compressed fuels such as for CNG require additional components for fuel storage and preparation for transportation mode consumption, the CompressedTransportationFuel also references energy and material inputs required for such preparation including fuel compression and storage – in this case, electrical energy from the local power grid as well as natural gas as the fuel's base element and compression input.

In addition to being referenced by each of the transportation modes considered in this model as well as for the supporting vehicle and road infrastructure, these objects are also aggregated in individual transportation mode and infrastructural analyses and water balances. These analysis elements are discussed in more detail in **Section 5.5**.

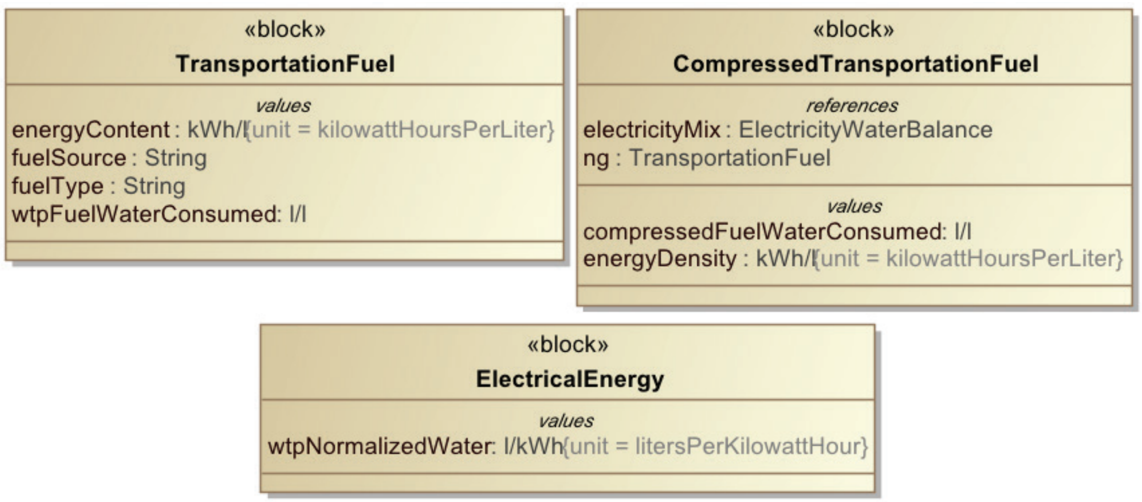


Figure 143. Energy Flows Representation in SysML Model.

A.3.1.2. Fluid Flows Definition

In addition to energy flows within this network representation, several fluid flows are also defined. In this model, fluids can either consist of base materials (ethylene glycol, petroleum, water, steam, and so on) or fluid compounds used for vehicles (lubricant, coolant, and other auxiliary fluids) that can be based on the previous set of fluids. These fluids are summarized in **Figure 144.**

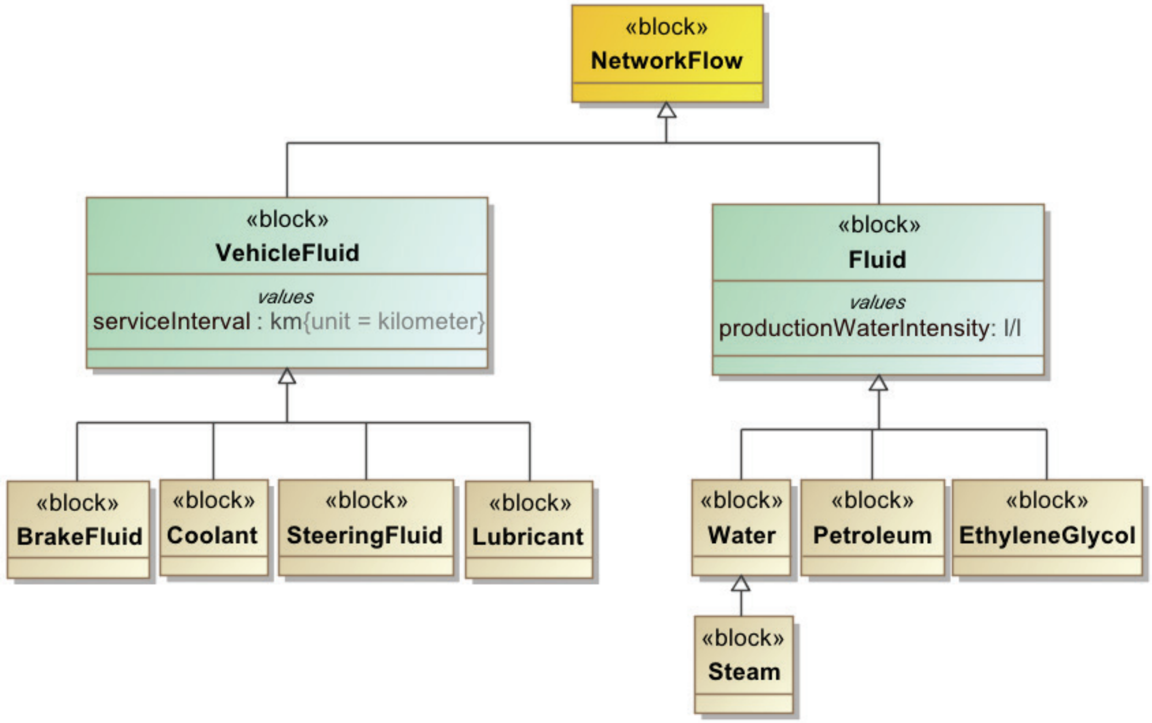


Figure 144. Fluid Flows Overview.

A.3.2. Functions Definition

A.3.2.1. Electricity Generation Functional Definitions and Allocations

The first set of functions to be defined for this model pertains to electricity generation, where the key activity of the electric grid in this network model is to **provide electricity**. This activity can be abstracted even further into two sub-activities: **distribute electricity** and **generate power**; the Generate Power function can be broken down even further into several actions pertaining to key steps in power plant operation, from heating and boiling water for steam generation to driving power plant turbines. These activities can be summarized in **Figure 145.**

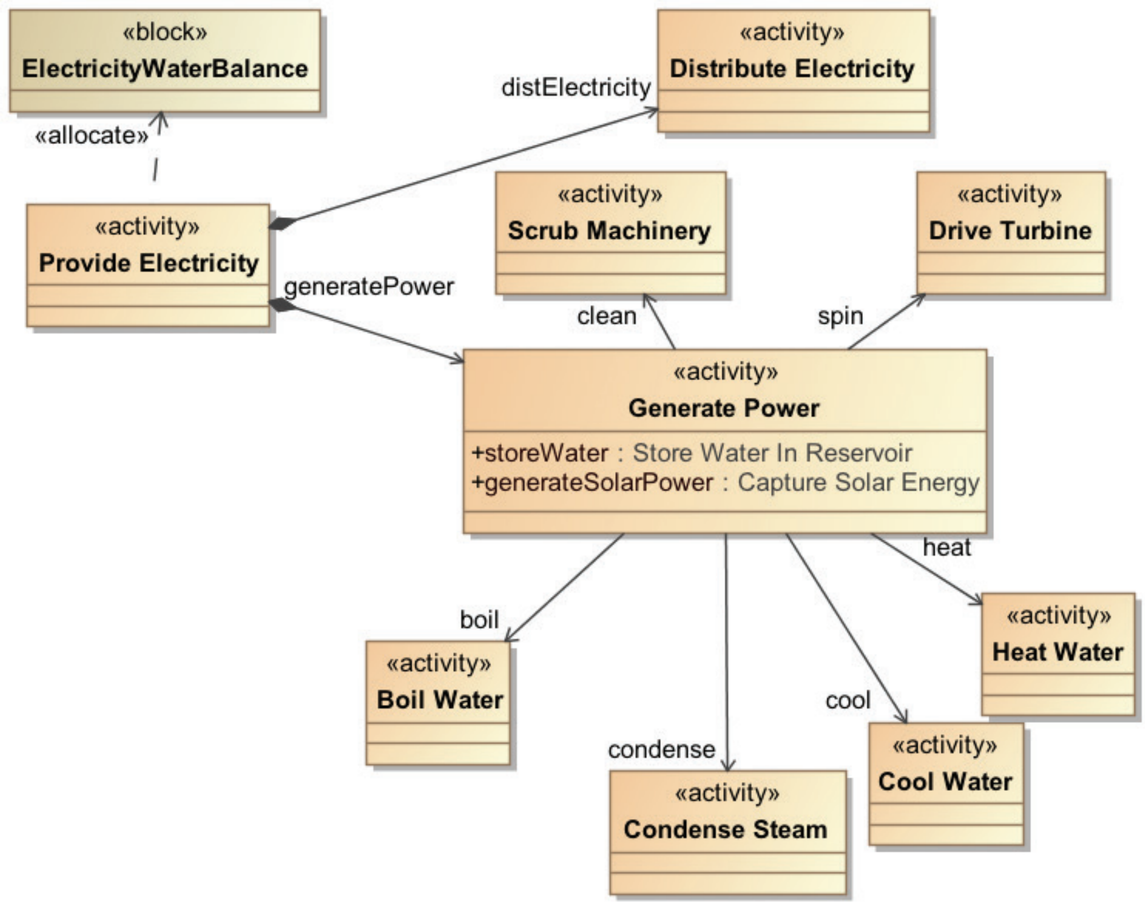


Figure 145. Electricity Generation Functions Overview.

These individual activities can ultimately be tied to specific structural components – in this case, individual plant operation activities can be allocated to specific plant machinery such as cooling towers and plant turbines. These allocations are summarized in **Figure 146**.

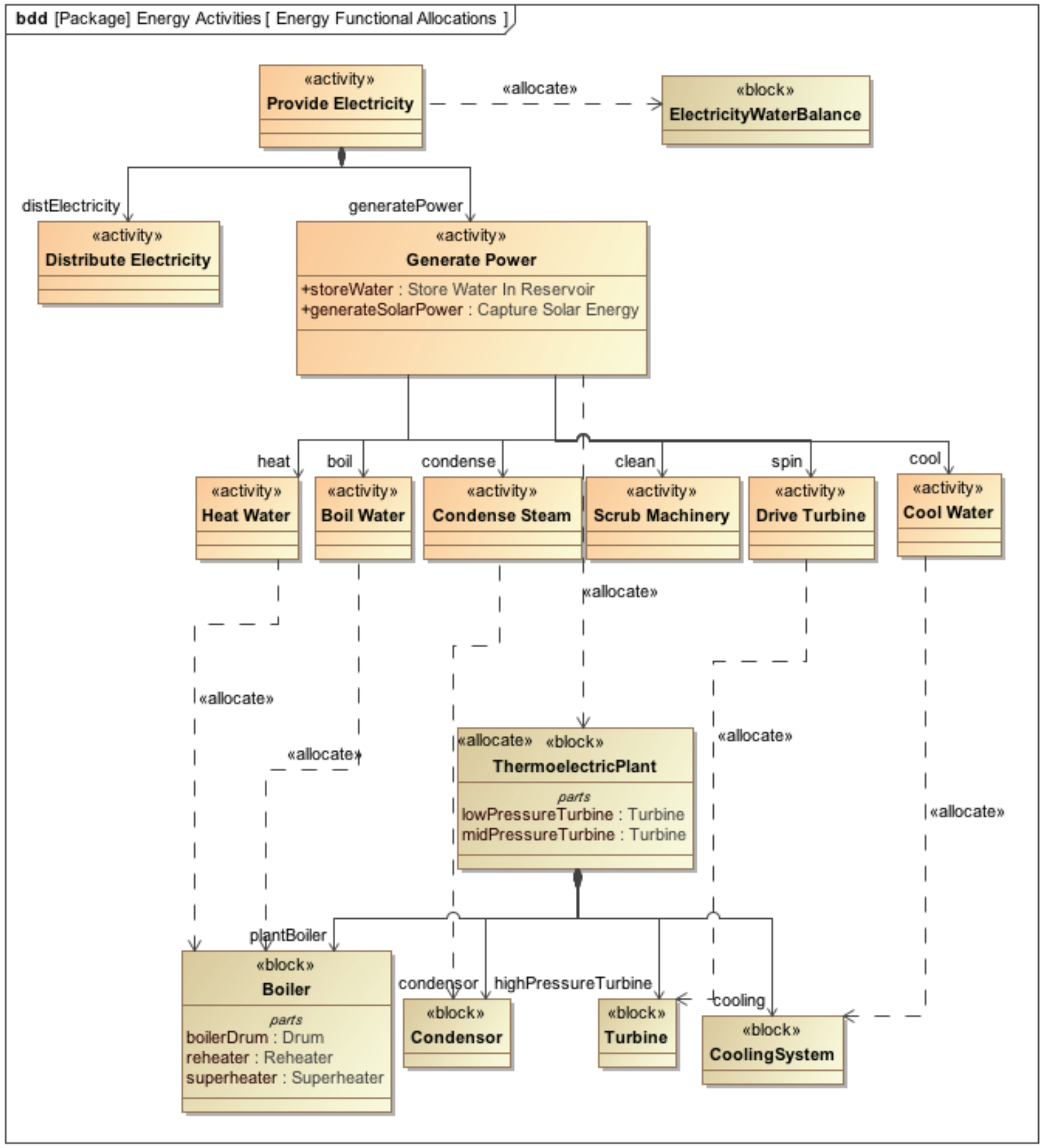


Figure 146. Electricity Generation Functional Allocations.

Individual activities can also be linked with each other using SysML activity diagrams; for electricity generation, both renewable and thermoelectric plants are considered. Individual material or energy flows such as thermoelectric fuels and water can be routed through a series of activities for each generation source as shown in **Figure 147**.

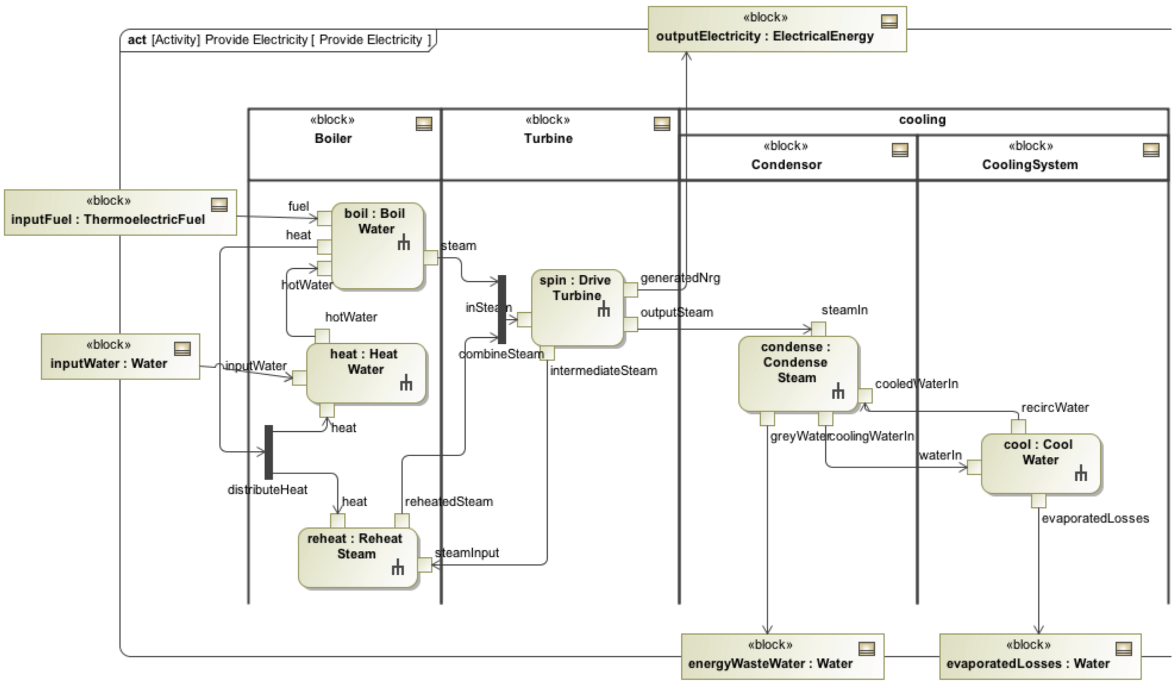


Figure 147. Activity Diagram of Thermoelectric Power Plant Functions and Object Flows.

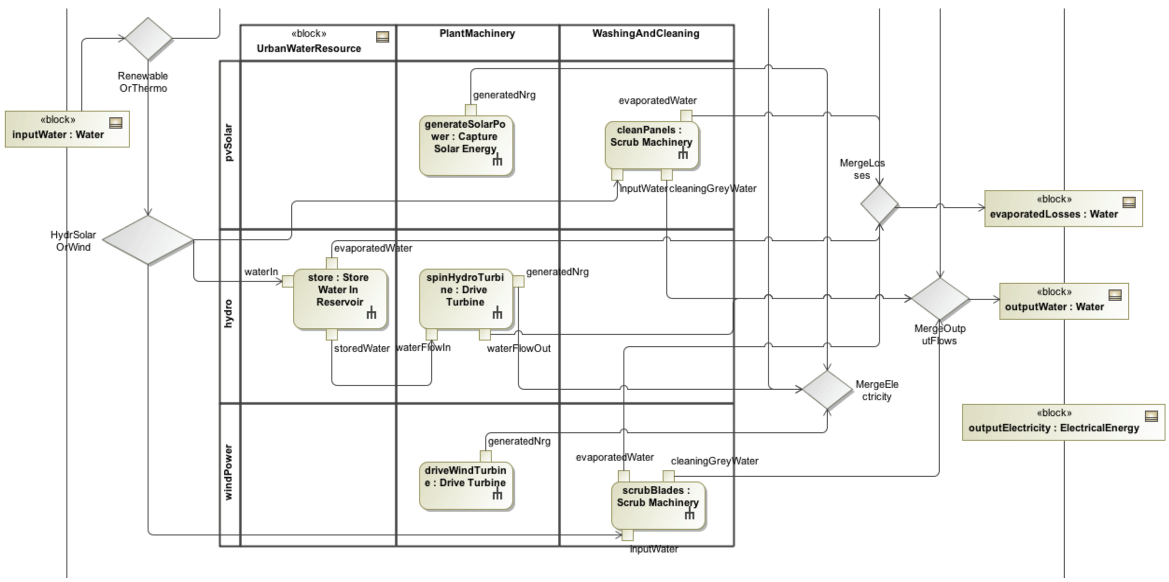


Figure 148. Activity Diagram of Renewable Power Plant Functions and Object Flows.

A.3.2.2. Fuel Production Functional Definitions and Allocations

Similar function decompositions can be made for the fuel production and distribution pathway in this model. **Figure 149** details the activities and sub-actions pertinent to the fuel production network in this transportation network representation.

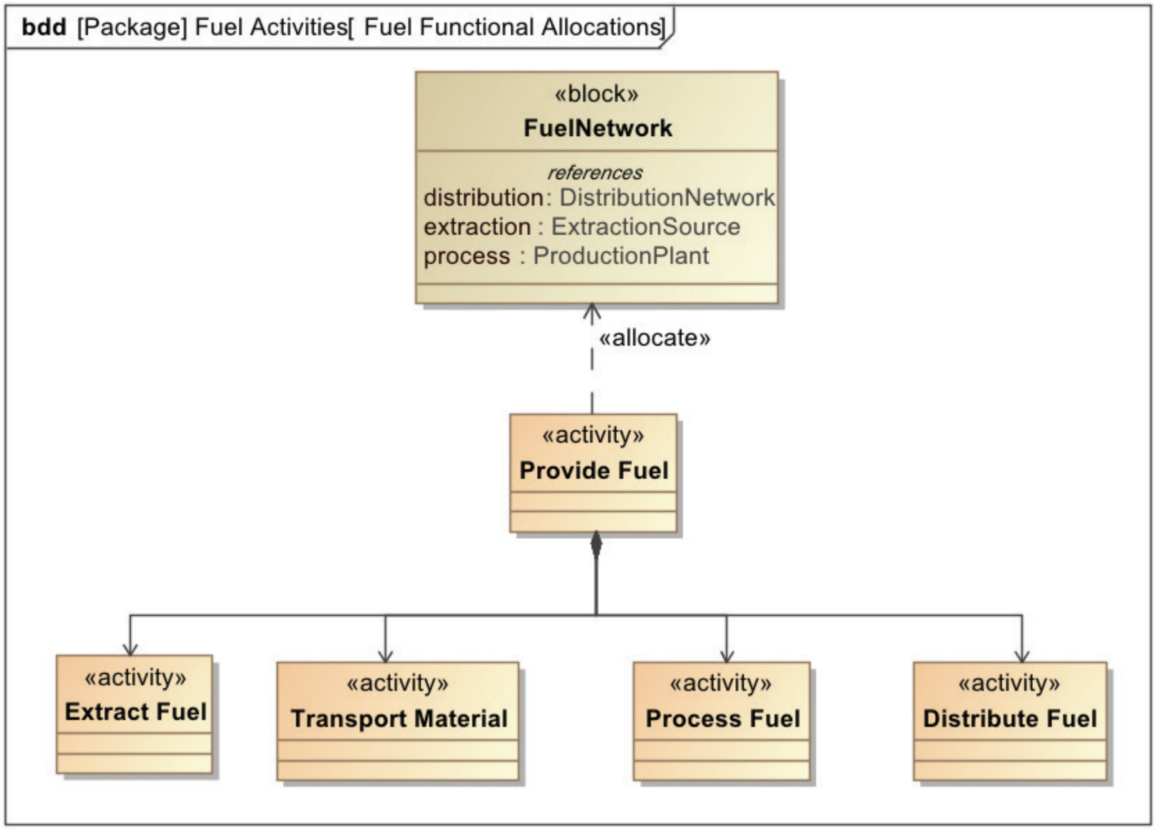


Figure 149. Associated Activities for Fuel Production and Distribution Network.

A.3.3. Physical Interactions and Internal Block Diagrams

Another capability of SysML is the ability to trace specific material and energy flows within certain model elements via internal block diagrams. The following figures highlight relationships between individual network flow elements and associated transportation modes and infrastructure.

A.3.3.1. Vehicle Mode Physical Allocations

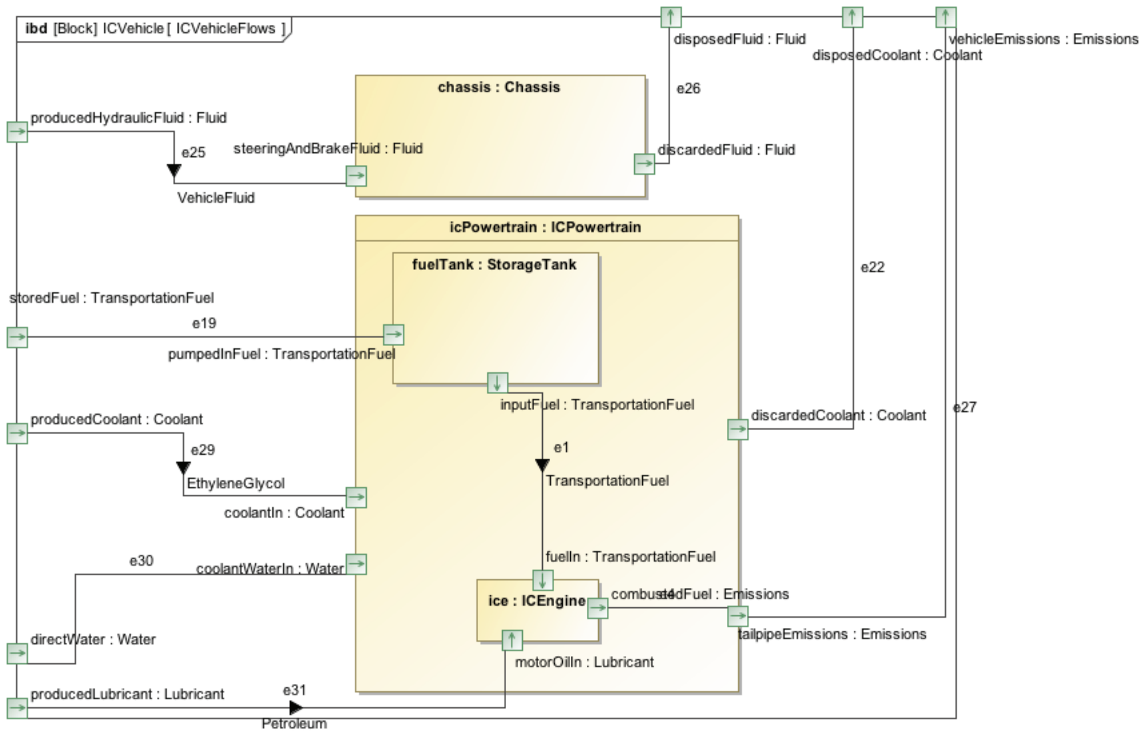


Figure 150. Network Flow Interactions For IC Vehicle Modes.

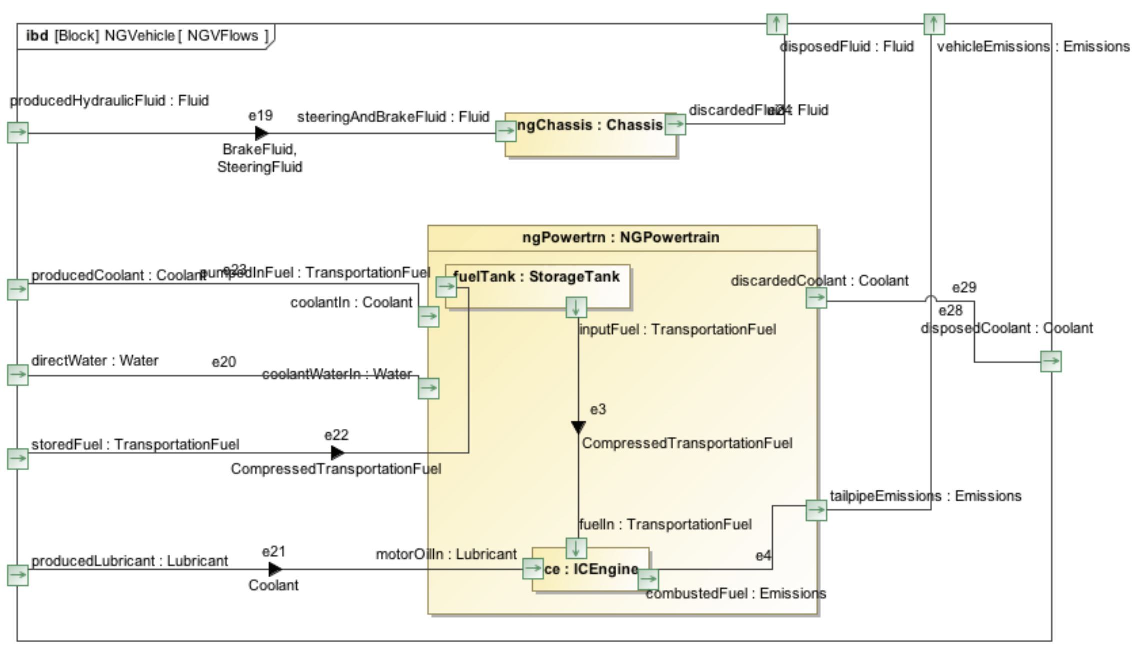


Figure 151. Network Flow Interactions For CNG-Fueled Vehicle Modes.

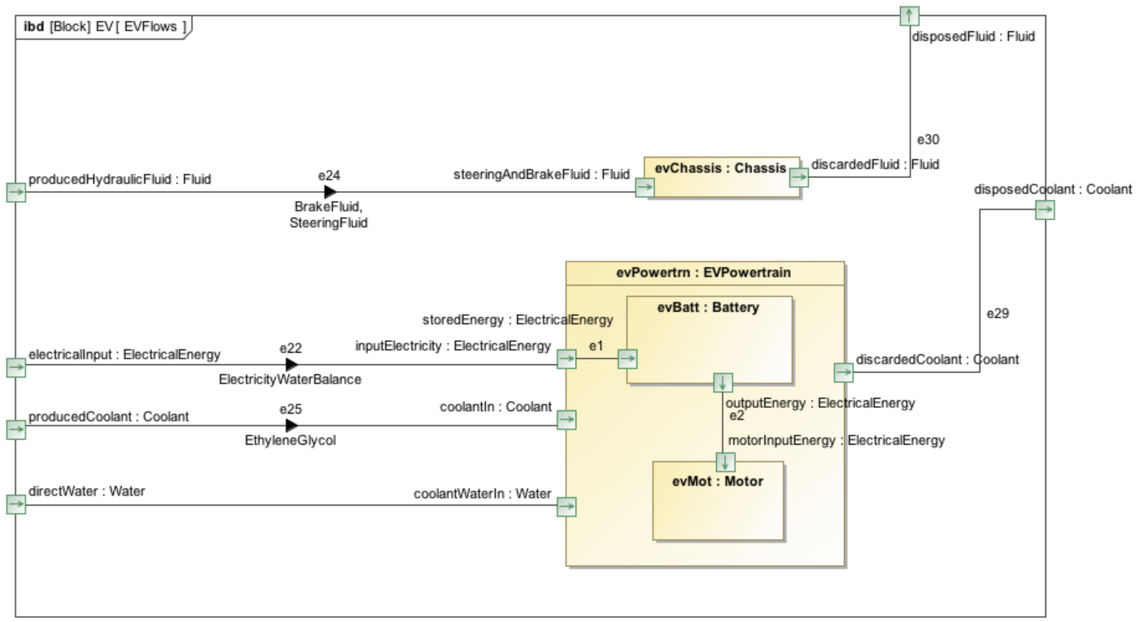


Figure 152. Network Flow Interactions For Electric Vehicle Modes.

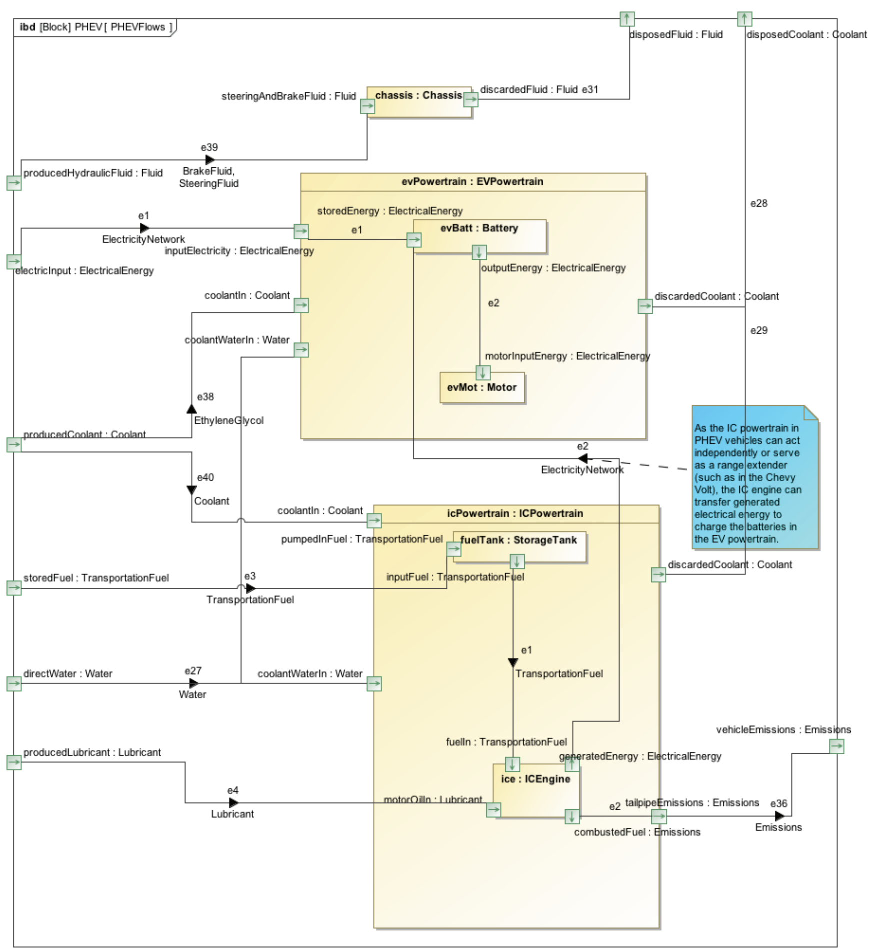


Figure 153. Network Flow Interactions For Plug-in Hybrid Electric Vehicle (PHEV) Modes.

A.3.3.2. Electricity Generation Physical Allocations

In addition to specifying activities and functions, object flows can be represented as item flows for the same set of components in internal block diagrams. One such non-trivial example pertains to thermoelectric power generation where there are numerous interactions between heating, turbine, and cooling components in these plants. **Figure 154** shows such physical interactions for a generic thermoelectric power plant.

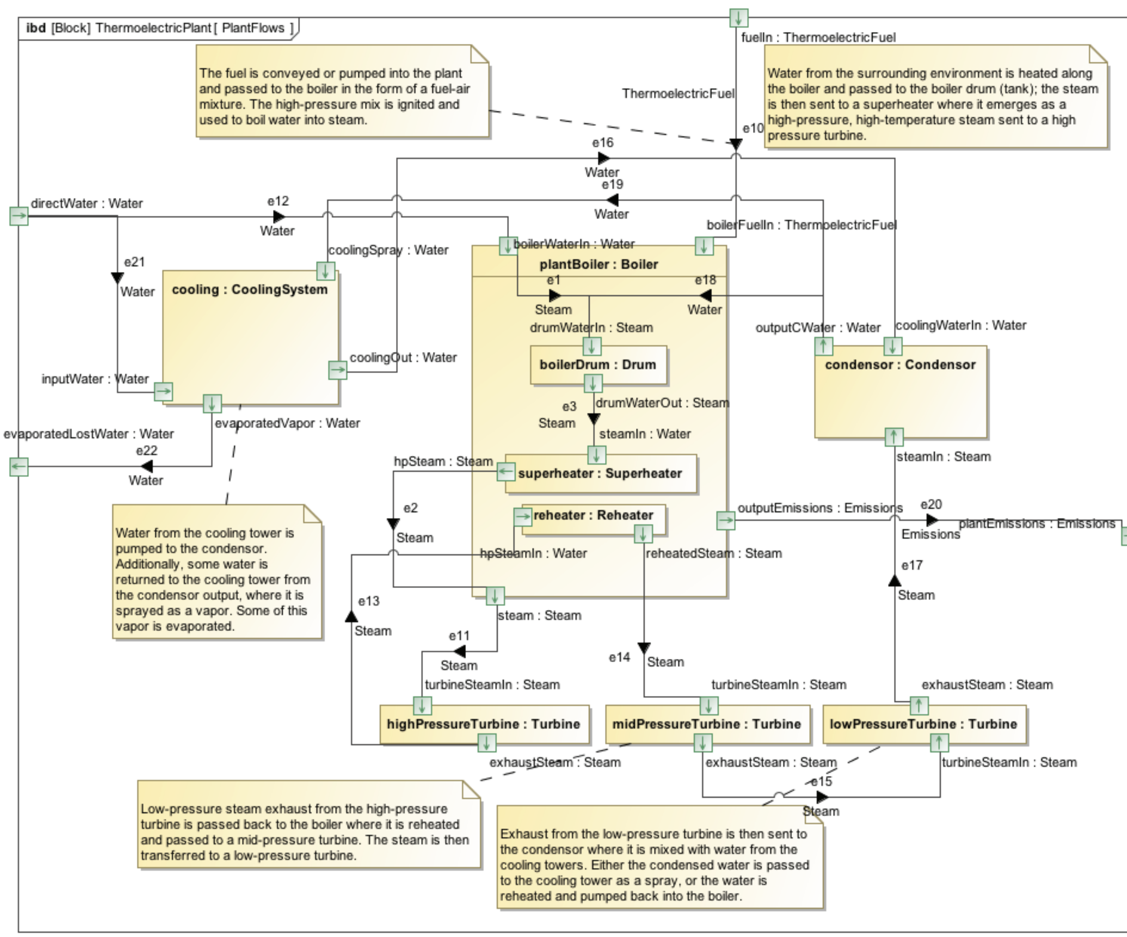


Figure 154. Physical Interactions of Thermoelectric Power Plant Components and Associated Flows.

A.3.3.3. Road Infrastructure Physical Allocations

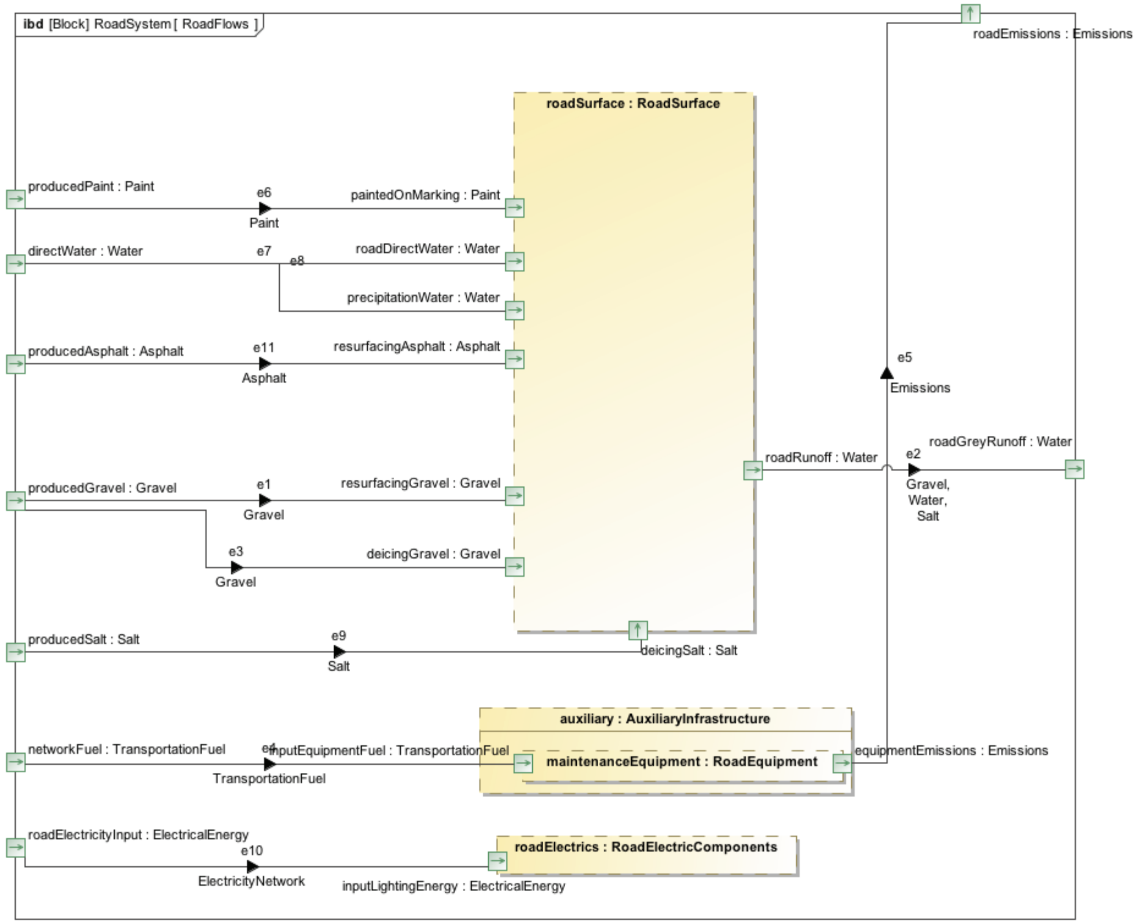


Figure 155. Road Infrastructure Operation and Maintenance Physical Interactions.

A.4. Additional SysML Model Diagrams and Components: Parametric Diagrams

While top-level parametric breakdowns are shown in Chapter 5, it should be noted that the analysis framework in this model consists of a multi-level approach to calculating water consumption for individual elements or subdomains and allocating them to determining network-level water consumption. The following sections highlight lower-level parametric diagrams not described in the preceding chapter.

A.4.1. Additional Individual Vehicle Mode Usage Analyses

A.4.1.1. PHEV Usage Water Consumption Analysis Breakdown

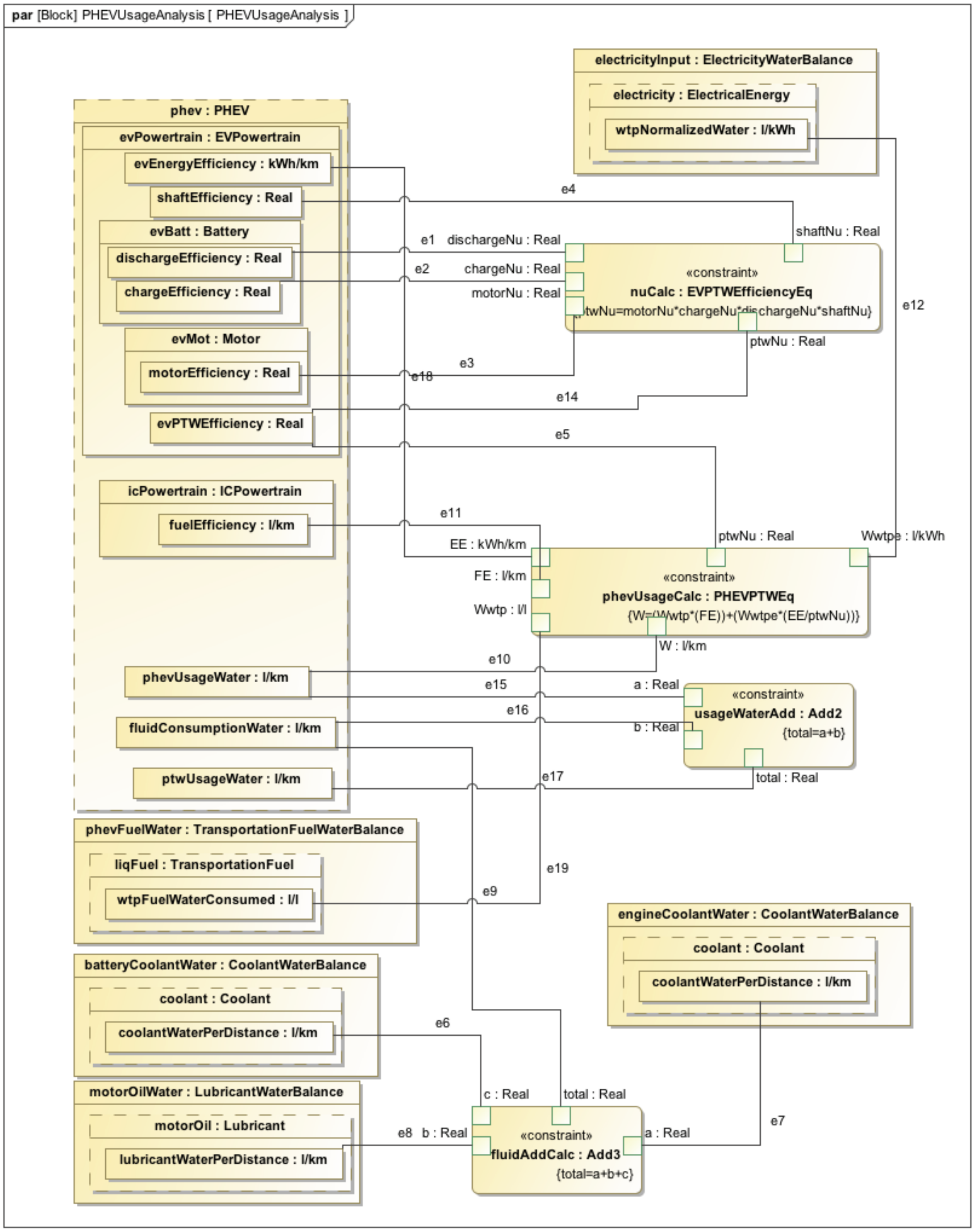


Figure 156. PHEV Usage Water Consumption Parametric Diagram.

A.4.1.2. Auxiliary Fluid Water Consumption Analysis Breakdown

Each vehicle mode analysis also contains lower-level water consumption analyses pertaining to the auxiliary fluids – in this case, engine lubricant and coolant – used in each vehicle. These analyses are grouped under **LubricantWaterBalance** and **CoolantWaterBalance**, as shown in **Figures 157** and **158**.

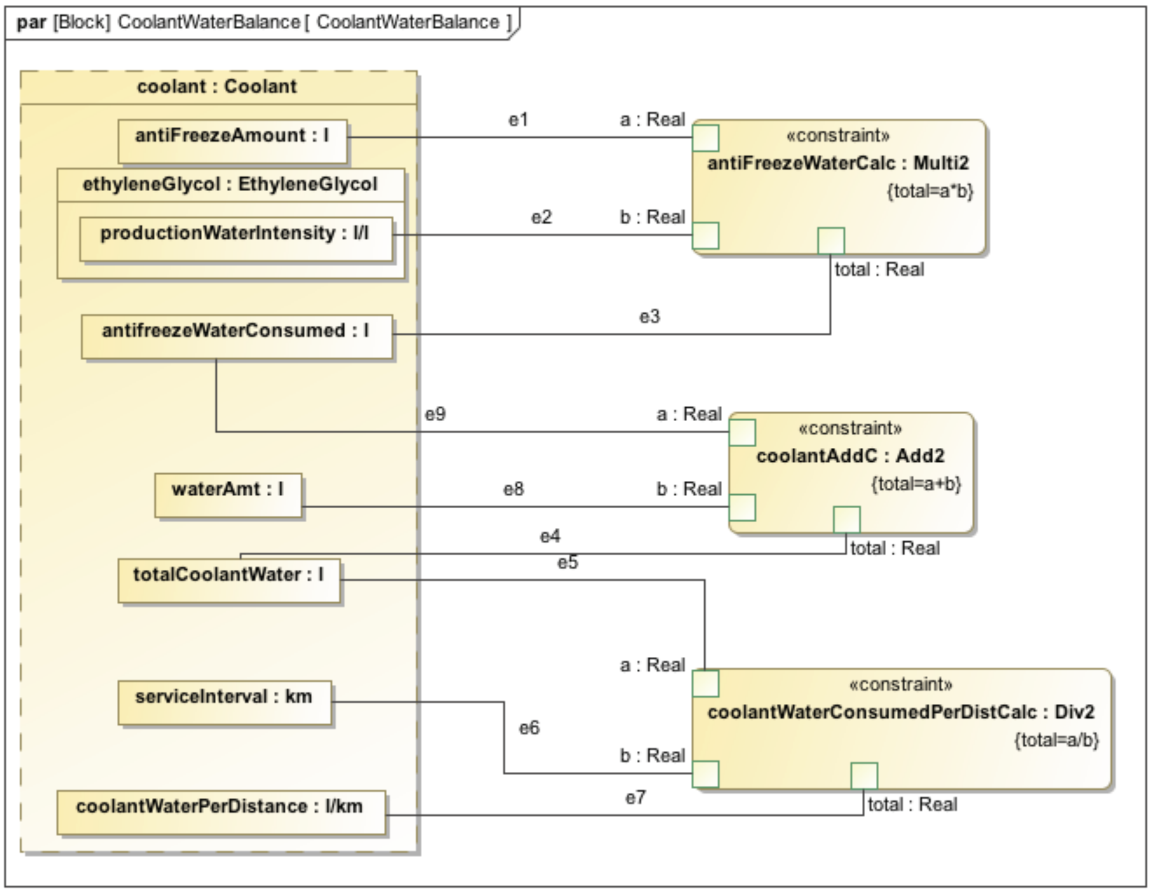


Figure 157. Engine Coolant Mixture Usage Water Consumption Parametric Diagram.

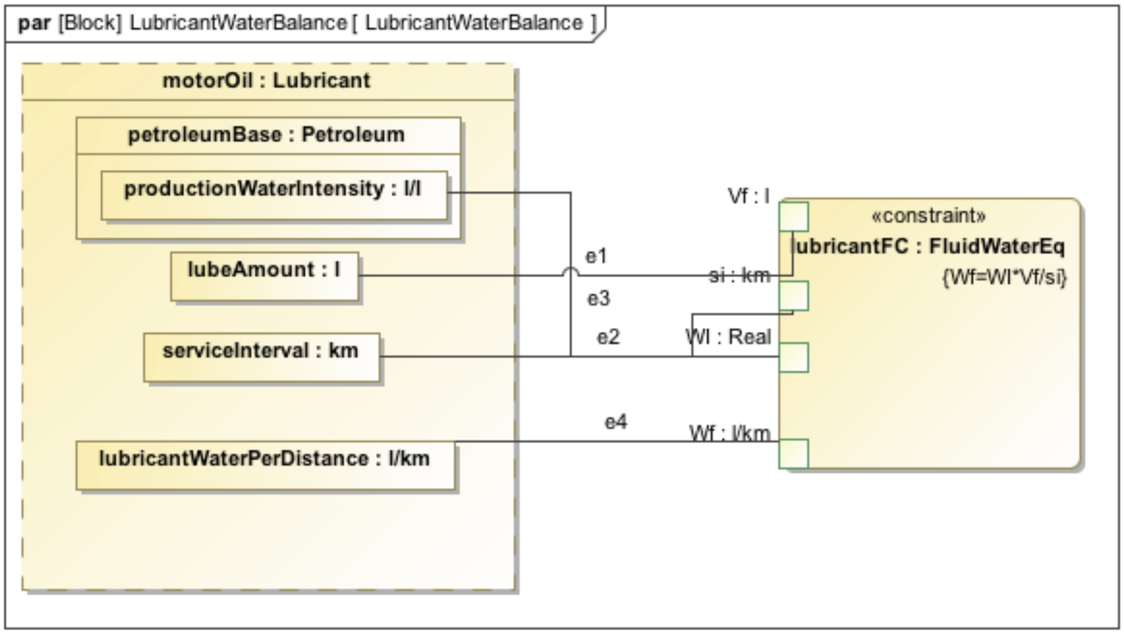


Figure 158. Engine Lubricant Usage Water Consumption Parametric Diagram.

A.4.2. Vehicle Fleet Usage Water Consumption Analyses

In addition to individual vehicle usage analyses described in Chapter 5 and in this Appendix, a parametric layout for each vehicle fleet in terms of combining individual vehicle mode water consumption values and respective market share values was defined. In this model, the aggregate water consumption for a given vehicle fleet also includes determining overall vehicle infrastructure operation water usage. The automobile fleet water consumption parametric layout is shown in **Figure 159**, while a similar bus fleet water consumption diagram is shown in **Figure 160**.

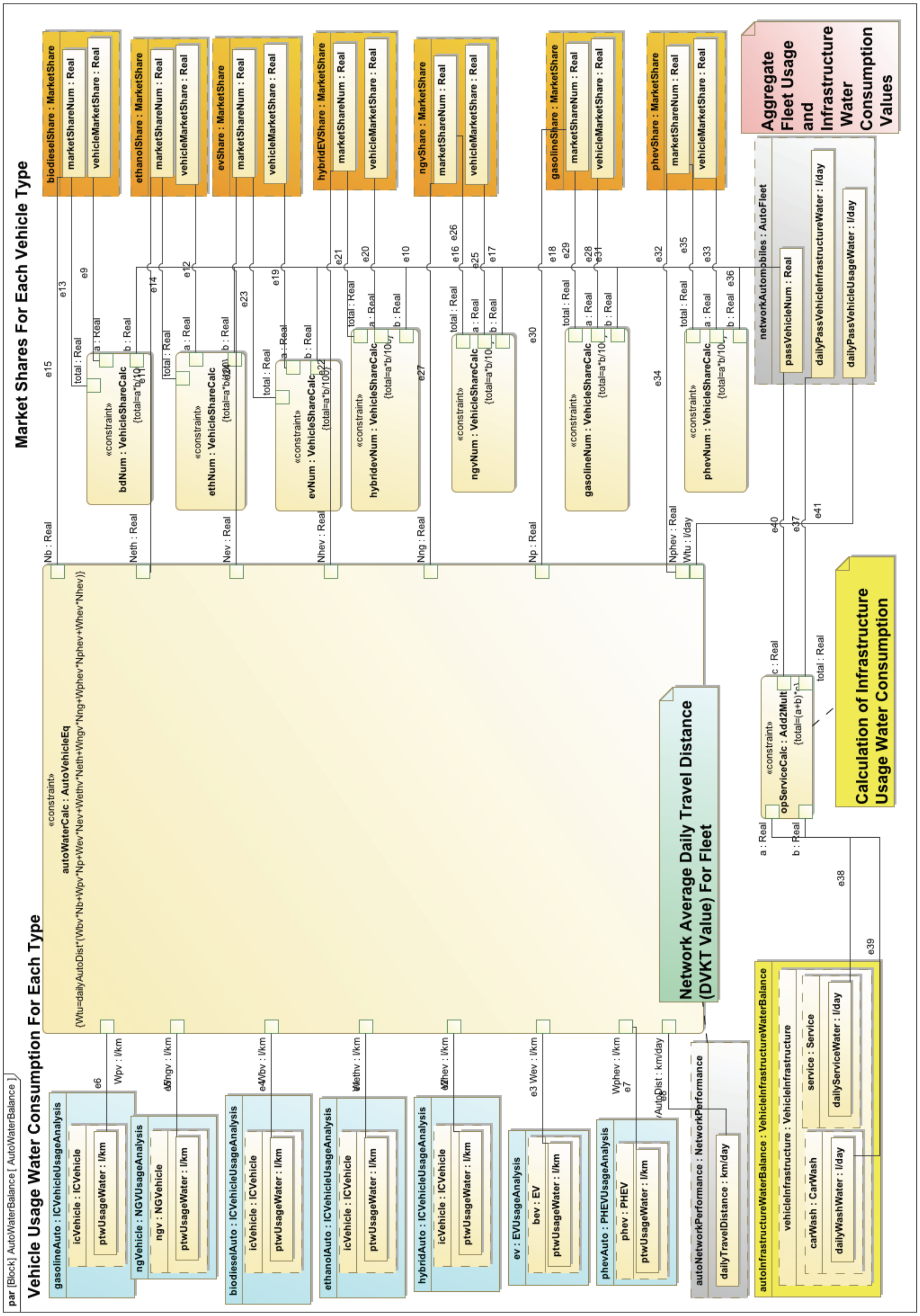


Figure 159. Water Consumption Balance for All Automobile Types and Infrastructure.

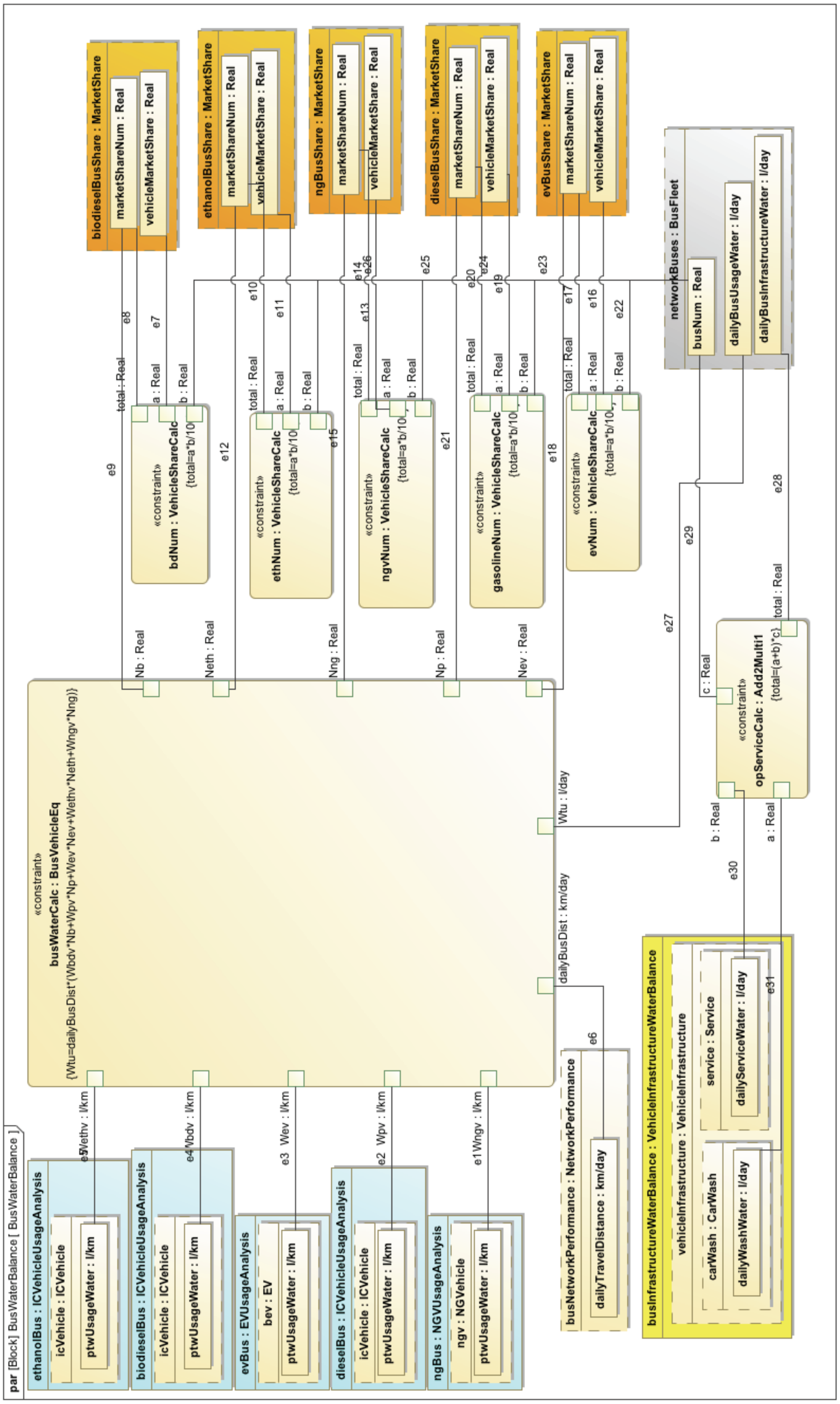


Figure 160. Water Consumption Balance for All Bus Types and Infrastructure.

A.4.3. Electricity Generation Water Consumption Analyses

In addition to allocating automobile and bus fleet water consumption separately as shown above, overall water consumption for electricity generation was broken down into determining aggregate water consumption values for all thermoelectric sources as well as for all renewable electricity generation sources. These associated parametric diagrams are shown below in **Figure 161** for thermoelectric generation and **162** for renewable sources.

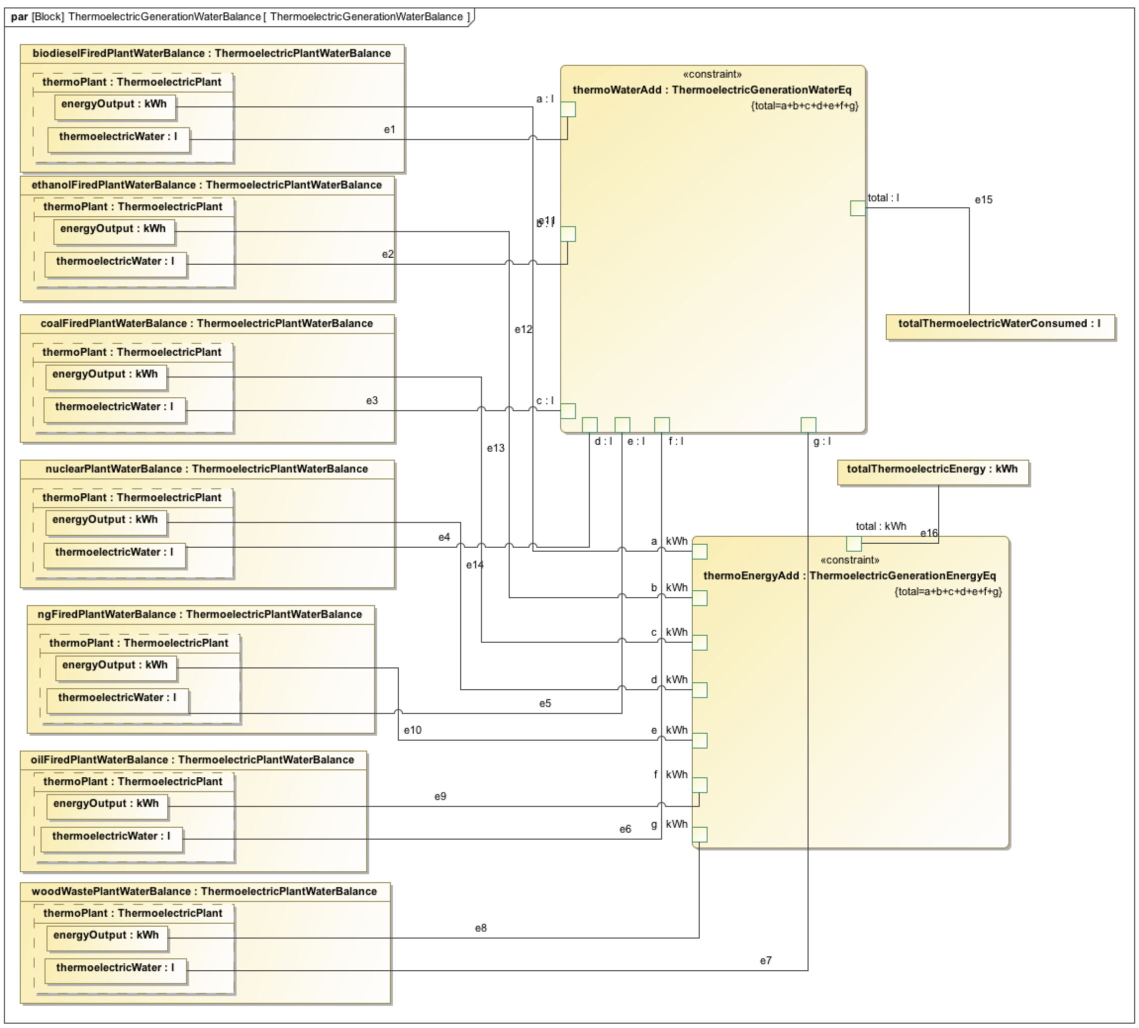


Figure 161. Water Consumption Balance For All Thermoelectric Generation Sources.

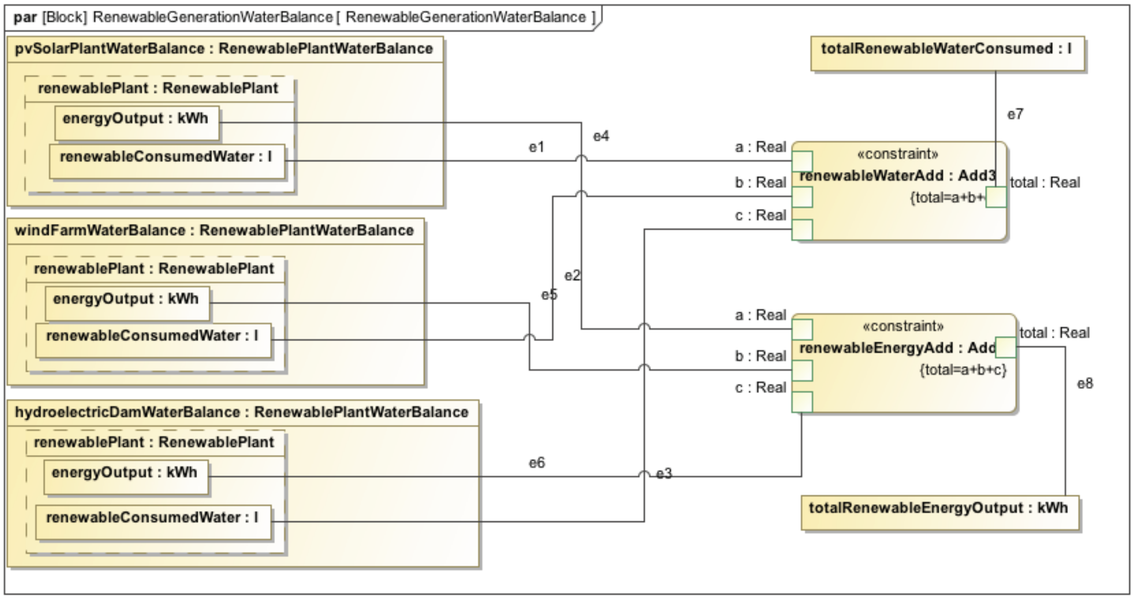


Figure 162. Water Consumption Balance For All Renewable Generation Sources.

A.4.4. Road Operation And Maintenance Water Consumption Analyses

A.4.4.1. Road Operation Water Balance

The first use-phase water balance analysis defined in this model focuses on the material and energy flows representing the operational inputs for a single road. As noted in the water consumption breakdown for road operation inputs presented in **Section 5.2**, the input value properties are traced to production water requirements for each group of materials or energy required for de-icing roads or operating road signage and lighting. These water consumption inputs are combined with energy and material consumption figures, from which they are linked to total output operation-related water consumption values via a series of common constraints as shown in **Figure 163**.

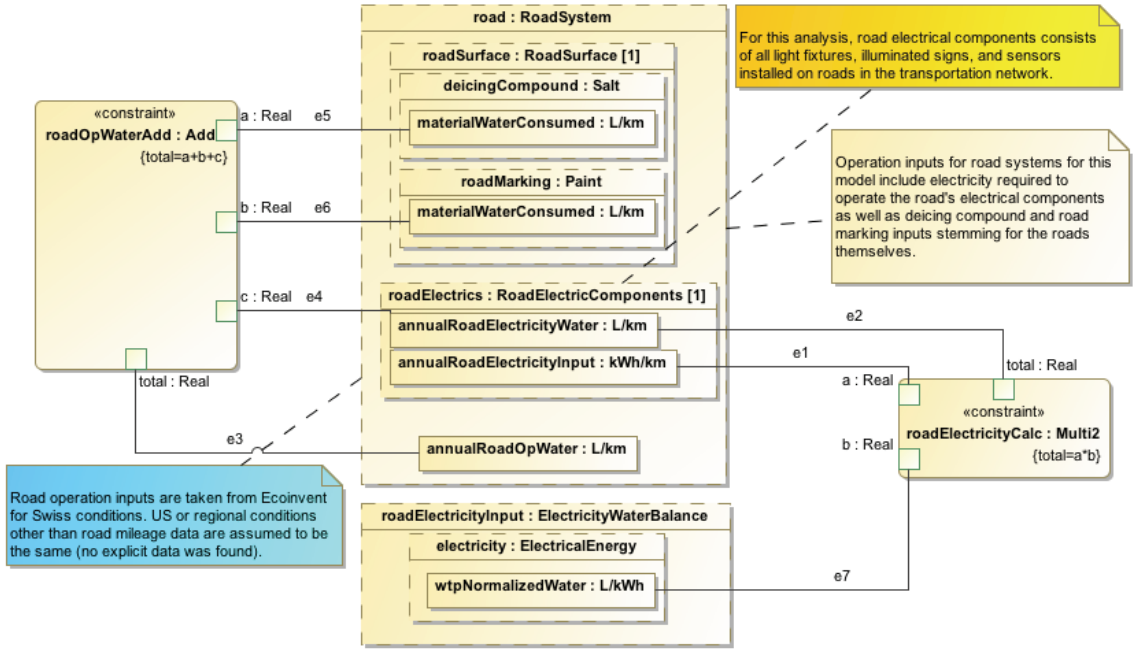


Figure 163. Road Operation Inputs Water Balance.

In addition to the RoadSystem block being aggregated in this analysis as well as the water consumption analysis pertaining to the network's electric grid, other internal references such as the road surface and associated operation-related inputs (paint for road markings and salt for de-icing operations in terms of materials and electricity consumption per kilometer of road distance) are included in the analysis as well. The water consumption inputs for associated materials are calculated from water intensity ratios and material consumption values for each kilometer of road as defined in Spielmann et al (2007).

A.4.4.2. Road Maintenance Water Balance

The water consumption analysis pertaining to maintenance inputs for the transportation network's road infrastructure follows a similar structure to that of the operational input water balance presented above. **Figure 164** shows the analysis layout for determining aggregate estimated values for maintenance-related water consumption, where the key inputs are water consumption values from the production of asphalt and gravel for road resurfacing, in addition to water requirements from the production of diesel required for heavy equipment and machinery associated with maintenance-related expenditures. As with the water consumption values for individual materials for operational inputs, material-related water consumption inputs are predetermined based on material consumption rates presented in Spielmann et al (2007).

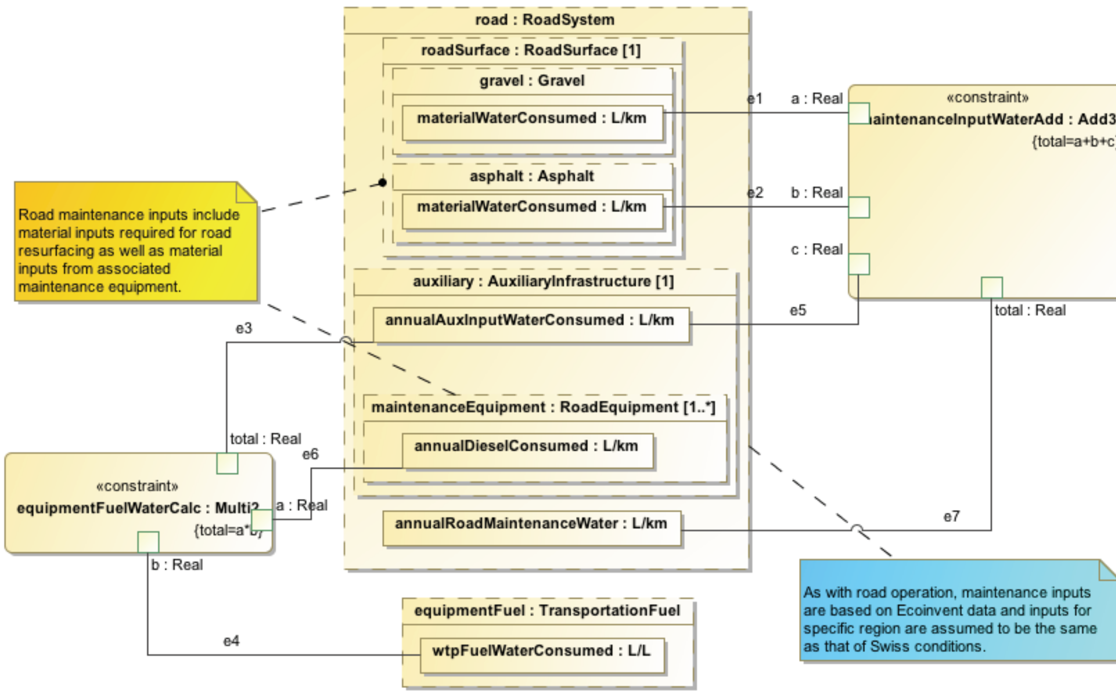


Figure 164. Road Maintenance Inputs Water Balance.

APPENDIX B

SCENARIO INPUTS AND RESULTS

B.1. Detailed Scenario Inputs

B.1.1. Annual Energy Outlook 2010 Reference Case Projections

Electricity generation, vehicle efficiency, and vehicle technology market share values for 2010 and 2030 are based on average fleet values in the United States as specified in the Annual Energy Outlook 2010 report provided by the Energy Information Administration. The increases in shares for each electricity share or vehicle technology type are then combined with regional transportation and energy statistics for each case. The inputs from the Annual Energy Outlook report are summarized below.

Table 67. AEO Reference Case Projections of Annual Electricity Capacity and Generation For 2010 and 2030 for Southeastern U.S. Electric Utilities (Energy Information Administration, 2010).

Electric Power Projections for EMM Region, Southeastern Electric Reliability Council				
Electricity Supply and Demand	2007	2008	2010 Reference Case	2030 Reference Case
Electricity Generating Capacity 1/ (gigawatts)				
Coal	71.271	71.271	71.667	73.571
Oil and Natural Gas Steam 2/	17.951	17.951	17.949	11.098
Combined Cycle	38.651	39.641	40.921	47.405
Combustion Turbine/Diesel	32.672	32.573	33.189	32.225
Nuclear Power	32.881	32.881	33.143	38.278
Pumped Storage/Other 3/	7.97	7.97	7.97	7.972
Fuel Cells	0	0	0	0
Renewable Sources 4/	12.426	12.431	12.455	12.515
Distributed Generation 5/	0	0	0	0
Total Capacity	**213.825**	**214.72**	**217.3**	**223.063**

Table 54 Continued. AEO Reference Case Projections of Annual Electricity Capacity and Generation For 2010 and 2030 for Southeastern U.S. Electric Utilities.

Electricity Supply and Demand	2007	2008	2010 Reference Case	2030 Reference Case
Generation by Fuel Type (billion kilowatthours)				
Coal	468.039	453.259	390.416	496.367
Petroleum	5.099	3.887	4.107	4.517
Natural Gas	127.706	121.367	143.529	133.364
Nuclear	258.006	256.119	263.880	304.117
Pumped Storage/Other 9/	-1.522	-1.995	-2.433	-2.415
Renewable Sources 10/	20.555	23.680	34.757	45.579
Total Generation	**877.883**	**856.317**	**834.256**	**981.529**

Table 68. AEO Reference Case Projections of Annual Electricity Capacity and Generation For 2010 and 2030 for Northwestern U.S. Electric Utilities (Energy Information Administration, 2010).

Electric Power Projections for EMM Region, Western Electricity Coordinating Council / Northwest Power Pool				
Electricity Supply and Demand	2007	2008	2010 Reference Case	2030 Reference Case
Electricity Generating Capacity 1/ (gigawatts)				
Coal	11.388	11.548	11.548	11.548
Oil and Natural Gas Steam 2/	0.7692	0.7692	0.76	0.76
Combined Cycle	6.131	6.731	7.285	9.867
Combustion Turbine/Diesel	2.0896	2.796	2.446	3.228
Nuclear Power	1.131	1.131	1.131	1.131
Pumped Storage/Other 3/	0.314	0.314	0.314	0.314
Fuel Cells	0	0	0	0
Renewable Sources 4/	37.249	38.031	42.994	40.645
Distributed Generation 5/	0	0	0	0
Total Capacity	**59.072**	**61.320**	**66.478**	**67.493**
Generation by Fuel Type (billion kilowatthours)				
Coal	82.336	83.804	390.416	496.367
Petroleum	0.564	0.499	4.107	4.517
Natural Gas	30.196	33.536	143.529	133.364
Nuclear	8.109	9.27	263.880	304.117
Pumped Storage/Other 9/	0.521	0.449	-2.433	-2.415
Renewable Sources 10/	138.031	139.443	34.757	45.579
Total Generation	**259.758**	**267.002**	**834.256**	**981.529**

Table 69. AEO Reference Case Projections of Annual Electricity Capacity and Generation For 2010 and 2030 for Aggregate United States Utilities (Energy Information Administration, 2010).

Electric Power Projections for EMM Region, United States				
Electricity Supply and Demand	**2007**	**2008**	**2010**	**2030**
			Reference Case	**Reference Case**
Electricity Generating Capacity 1/ (gigawatts)				
Coal	309.015	308.379	309.015	308.378
Oil and Natural Gas Steam 2/	116.555	115.874	116.555	115.874
Combined Cycle	182.578	188.158	182.578	188.158
Combustion Turbine/Diesel	133.207	134.639	133.207	134.639
Nuclear Power	100.544	100.558	100.544	100.558
Pumped Storage/Other 3/	21.833	21.833	21.833	21.833
Fuel Cells	0.0016	0.0016	0.0016	0.0016
Renewable Sources 4/	101.139	110.01	101.139	110.013
Distributed Generation 5/	0	0	0	0
Total Capacity	**964.872**	**979.456**	**964.872**	**979.456**
Generation by Fuel Type (billion kilowatthours)				
Coal	1998.391	1976.174	1806.155	2164.011
Petroleum	61.307	42.302	40.448	43.491
Natural Gas	814.766	798.535	779.624	885.543
Nuclear	806.424	806.182	812.687	885.931
Pumped Storage/Other 9/	4.0820	4.00144	0.508	0.586
Renewable Sources 10/	319.544	338.782	424.180	670.778
Total Generation	**4004.514**	**3965.976**	**3863.602**	**4650.398**

Table 70. AEO Reference Case Projections of Light-Duty Vehicle Miles Per Gallon For 2010 and 2030 for Aggregate Automobile Fleet (by Technology) (Energy Information Administration, 2010).

Light-Duty Vehicle Miles per Gallon by Technology Type (miles per gallon gasoline equivalent)				
Technology Type	2007	2008	2010 Reference Case	2030 Reference Case
Conventional Cars				
Gasoline ICE Vehicles	31.05	31.152	31.290	38.65
TDI Diesel ICE	38.24	38.262	38.317	45.57
Alternative-Fuel Cars				
Ethanol-Flex Fuel ICE	30.45	30.40	31.45	38.86
Plug-in 10 Gasoline Hybrid	n/a			58.66
Plug-in 40 Gasoline Hybrid				67.71
Electric-Gasoline Hybrid	46.27	46.196	44.38	52.45
Compressed Natural Gas ICE	31.39	31.48	31.58	38.91

Table 71. AEO Reference Case Projections of Light-Duty Vehicle Stocks And Market Shares (by Technology) (Energy Information Administration, 2010).

Light-Duty Vehicle Stock by Technology Type (millions)				
Existing Vehicle Fleet				
Technology Type	2007	2008	2010 Reference Case	2030 Reference Case
Conventional Cars				
Gasoline ICE Vehicles	132.5479	131.0585	124.4925	127.53
TDI Diesel ICE	0.509	0.482	0.432	3.39
Alternative-Fuel Cars				
Ethanol-Flex Fuel ICE	0.994	1.389	2.249	23.968
Plug-in 10 Gasoline Hybrid	n/a			2.001
Plug-in 40 Gasoline Hybrid				0.649
Electric-Gasoline Hybrid	0.722	0.971	1.382	12.529
Compressed Natural Gas ICE	0.0112	0.0111	0.011	0.0215
Electric Vehicles	0.0265	0.0254	0.0230	0.00354

B.1.1.1. Bus Fuel Efficiency Values

Table 72. Bus Fuel Economy and Efficiency Values For This Case Study, 2010 Conditions (Weststart-CALSTART, 2006).

Vehicle Technology Type	Fuel Economy, mpg	Fuel Efficiency, l/km
Diesel (New Flyer D40LF – Allison, ZF, or Voith powertrain)	4.4	0.5346
Diesel Hybrid (Allison Electric Drive E^V)	5.5	0.4277
CNG (New Flyer D40LF - Cummins)	3.2	0.7841
Ethanol	Assumed to be 4.4	0.5346
Biodiesel	4.4	0.5346

B.1.2. Automobile and Bus Fleet Amount Derivations

The total number of automobiles for the Atlanta metro area was estimated based on the number of registered vehicles within each county within the metropolitan region. **Table 73** summarizes the total number of automobiles for each county. It should be noted that these numbers do not account for actively-used versus unused vehicles, and these numbers include all passenger vehicles and other light-duty vehicles – such as trucks – with no delineation of vehicle configurations available.

Table 73. Number of Registered Vehicles In Atlanta Metro Area By County, As Of October 2010 (Georgia Department of Revenue, 2010).

Registered Vehicles By County As Of 10/31/2010	
County	**Number Of Vehicles**
Fulton	542,837
DeKalb	381,468
Gwinnett	469,283
Cobb	424,624
Clayton	129,900
Intermediate Value	**1,948,112**
Cherokee	126,607
Douglas	69,754
Fayette	72,805
Henry	112,940
Rockdale	45,373
Total	**2,375,671**

Table 74. MARTA Bus Fleet Numbers and Usage Statistics, 2009 Fiscal Year (Metropolitan Atlanta Rapid Transit Authority, 2009).

Data Type	Value
Active Buses in Service, # buses	615
Average Vehicle Age, years	7.8
Number of Bus Routes	130
Number of Bus Stop Locations	11,482
Number of Bus Shelters	741
Annual Bus Passenger Miles, miles	527,000,000
Population Served, passengers	1,689,100
Miles of Bus Route, miles	1765

B.1.3. Auxiliary Fluid Inputs for All Scenarios

Tables 75 to 77 summarize water consumption results of the auxiliary fluid flows for all vehicles considered in this mobility network model. It is assumed that these fluid amounts are constant in all scenarios, although some vehicles are not considered in certain scenarios, such as the lack of PHEVs in the 2010 baseline and Washington State scenarios. As there is not enough data pertaining to the amount of coolant used in buses, the amounts for automobiles are used in place of bus coolant values. For this model, it is assumed that the base material for engine lubricants is that of petroleum. The base material used for the production of antifreeze is assumed to be that of ethylene glycol, with water intensity values taken from Althaus et al (2007) (Althaus et al, 2007).

Table 75. Engine Lubricant Water Consumption Amounts for Passenger Vehicles by Technology Type.

Vehicle Technology Type	Lubricant Amount, l	Service Interval, km	Water Intensity (Assumed from Petroleum), l/l	Water Consumed Per Distance, l/km
Internal Combustion	3.7854	12,000	7.08	0.002234
Electric Vehicles	n/a	n/a		n/a
PHEV	3.7854	12,000		0.002234
CNG-Fueled	3.7854	18,000		0.001489

Table 76. Coolant Water Consumption Amounts for Passenger Vehicles by Technology Type.

Vehicle Technology Type	Coolant Antifreeze Amt, l	Coolant Water Amt, l	Service Interval, km	Water Intensity (Ethylene Glycol), l/l	Antifreeze Water Consumed, l	Water Consumed Per Distance, l/km
Internal Combustion	2.7	2.7	48,000	5.461	14.745	
Electric Vehicles	2.7	2.7	48,000			
PHEV	2.7	2.7	48,000			

Table 77. Engine Lubricant Water Consumption Amounts for Buses by Technology Type.

Vehicle Technology Type	Lubricant Amount, l	Service Interval, km	Water Intensity (Assumed from Petroleum), l/l	Water Consumed Per Distance, l/km
Internal Combustion	27.958	12,000	7.08	0.016

B.1.4. Vehicle Washing Water Consumption Inputs

Table 78. Water Usage For Car Wash Facilities In Orlando, Boston, and Phoenix (Brown, 2002).

Total Water Usage	Orlando (gallons/vehicle)	Boston (gallons/vehicle)	Phoenix (gallons/vehicle)	Average Usage By Technology
Self Serve	16	15.2	12.3	**15**
In-Bay	24.6	40	72.5	**42.9**
Conveyor	34.3	26.7	43.8	**34**
Average City Usage	**27.2**	**24.5**	**42.5**	

Table 79. Water Evaporation/Carryout Rates For Car Wash Facilities In Orlando, Boston, and Phoenix (Brown, 2002).

Evaporation/ Carryout	Orlando Facilities (%)	Boston Facilities (%)	Phoenix Facilities (%)	Average % By Technology
Self Serve	22.9	33.2	19.8	**25.3**
In-Bay	29.8	28.6	32.8	**30.2**
Conveyor	15.1	16.1	16.7	**17.6**

Table 80. Water Consumed (Based on Evaporation and Carryout) For Car Wash Facilities (Brown, 2002).

Water Consumption	Orlando Facilities (gallons/vehicle)	Boston Facilities (gallons/vehicle)	Phoenix Facilities (gallons/vehicle)	Average Consumption By Technology	
				Gallons /vehicle	Liters /vehicle
Self Serve	3.66	5.05	2.44	**3.795**	**14.366**
In-Bay	7.33	11.44	23.78	**12.956**	**49.043**
Conveyor	5.18	4.30	7.31	**5.984**	**22.652**

B.1.5. Water Usage Findings for Electricity Generation and Thermoelectric Fuels Production

Tables 81 to 85 outline the water usage values for electricity generation and fuel production based on the water consumption values outlined in **Section 3.2.1.**

Table 81. Summary of Water Usage Findings for Coal-Fired and IGCC Power Plants By Configuration/Technology (Fthenakis et al, 2010).

Fuel	Cooling Config	Boiler Type	Data Sourcing	Site Water Used, l/kWh
Coal	Once-Through	Subcritical	NETL Projections 2009	103
		Supercritical	EPRI Projections	85.6
		N/A	NETL Projections 2009	76-119
	Cooling Pond	Subcritical	NETL Projections 2009	67.8
		Supercritical		57.2
		N/A	EPRI Projections	1.1-2.3
	Cooling Tower	Subcritical	NETL Projections 2009	2.01
			NETL Baseline 2007	2.59
			NETL 2005 Study	4.43
		Supercritical	NETL Projections 2009	2.5
			NETL 2005 Study	3.94
			NETL Baseline 2007	2.27
		N/A	EPRI Projections	1.9-2.3

Table 82. Summary of Water Usage Findings for Oil and Natural Gas Power Plants By Configuration/Technology (Fthenakis et al, 2010).

Fuel	Cooling Configuration	Data Sourcing	Site Water Used, l/kWh
Oil or NG	Once-Through	NETL 2009	85.9
	Cooling Pond	NETL 2009	29.9
	Cooling Tower	NETL 2009	0.95
NGCC	Once-Through	NETL 2009	34.1
		EPRI	28-76
	Cooling Pond	NETL 2009	22.5
	Cooling Tower	NETL 2009	0.568
		NETL 2007	1.03
		NETL 2005	1.9
		EPRI	0.87
	Dry Cool	NETL 2009	0.015

Table 83. Summary of Water Usage Findings for Biomasss Power Plants By Configuration/Technology (Berndes, 2002).

Biofuel	Cooling Config	Water Used, l/kWh
Biomass	Steam Plant	1.8
	Cooling Tower	2.1
	Dry Cool	0.15

Table 84. Summary of Water Usage Findings for Hydroelectric and Renewable Power Plants By Configuration/Technology (Fthenakis et al, 2010).

Plant	Location	Site Water Used, l/kWh
Hydro	United States Avg	0 (Withdrawn) 17 (Consumed)
	California Median	0 (Withdrawn) 0.038-210 (Consumed)
	California Mean	0 (Withdrawn) 5.3 (Consumed)
PV Solar		0.015
Wind		0.004

Table 85. Summary of Water Usage Findings for Thermoelectric Fuels Production (Fthenakis et al, 2010).

Fuel	Process	Sub-Process	Technology	Site Water Used, l/kWh
Coal	Mining	Eastern U.S. Surface		0.19
		Eastern U.S. Underground		0.38
		U.S. Average		
	Processing	Beneficiation		≥ 0.045
	Transport	Slurry Pipeline		0.45
Uranium	Mining	Average		0.038
	Processing	Milling		0.019
		Conversion	Uranium Hexafluoride	0.015
		Enrichment	Gaseous Diffusion	0.079
			Gas Centrifuge	0.008
			Fabrication	0.003
Natural Gas	Extraction	On-Shore		0.130
		Off-Shore		0.0008
	Processing	Purification		0.064
	Transport	Pipeline		0.0015

B.2. Detailed Scenario Results

B.2.1. Detailed Results for 2010 Baseline Scenario

Table 86. Automobile Fleet Usage Water Consumption Results, 2010 Base Case.

Auto-mobile Type	Fuel Usage Water, l/km	Fluid Cons-umption Water, l/km	Total Usage Water, l/km	Number of Vehicles	Total Usage Water, Aggregate, l/km	DVKT, km/day	Total Daily Travel Usage Water, Aggregate, l/day
Biodiesel	0.833	0.003	0.83	0	0	44.9	0
Corn Ethanol	1.353	0.003	1.356	119972	162,682.03		7,304,423.24
Gasoline	0.136	0.003	0.139	2158060	299,970.34		13,468,668.3
CNG	0.04	0.002	0.042	9266	389.172		17,473.83
EV	2.3159	0.0004	2.316	238	551.208		24,749.24
HEV	0.0945	0.003	0.097	75784	7351.048		330,062.06
PHEV	2.045	0.003	2.049	0	0		0
Total							21,145,376.6

Table 87. Automobile Fleet Usage Water Consumption Results, 2010 Base Case.

Bus Type	Fuel Usage Water, l/km	Fluid Cons-umption Water, l/km	Total Usage Water, l/km	Number of Vehicles	Total Usage Water, Aggregate, l/km	DVKT, km/day	Total Daily Travel Usage Water, Aggregate, l/day
Biodiesel	7.42	0.017	7.437	0	0	237.5	0
Corn Ethanol	9.238	0.017	9.255	0	0		0
CNG	0.391	0.017	0.407	454	184.778		43,884.775
EV	4.660	0.001	4.661	0	0		0
Diesel	0.929	0.017	0.946	161	152.306		36,172.675

Table 88. Electricity Generation Water Consumption Results, 2010 Base Case.

Electricity Source	Fuel Water, l/kWh	Plant Operation Water, l/kWh	Total Water, l (per month)
Coal	0.45	2.6	14,990,000,000
Oil	0.09	0.61	5,600,000
NGCC	0.087	1.02	1,501,000,000
Nuclear	0.132	3.2	10,099,000,000
Hydro	0	179.5	3.34E+10
PV Solar	0	0.022	0
Wind	0	0.004	0
Wood Waste Biomass	0	1.8	466,200,000
Corn Ethanol	16.052	1.7	0
Biodiesel	5.507	1.7	0
Total	*Thermo*	27,065,934,000	
	Renewable	3.34E+10	
	Total	6.05E+10	
	Normalized	6.736	

Table 89. Total Road Infrastructure Operation Water Consumption Results, 2010 Base Case.

Road	Annual Maintenance Per Distance, l/km	Annual Operation Per Distance, l/km	Total Daily Maintenance Water, l/day	Total Daily Operation Water, l/day	Total Daily Water, l/day	Distance, km
Highway	0.011	871.44	0.139	11,219.382	11,219.521	4,700.8
Arterial	0.003	229.364	0.129	8745.243	8,745.372	13,916.8
Collector	0.003	64.285	0.079	1496.636	1,496.715	8,497.6
Total					21,461.608	

Table 90. Road Infrastructure Maintenance Water Consumption Results, 2010 Base Case.

Road Maintenance	Annual Equipment Water, l/km	Annual Asphalt Water, l/km	Annual Gravel Water, l/km
Highway	0.0108	Not Considered	Not Considered
Arterial	0.003	Not Considered	Not Considered
Collector	0.0034	Not Considered	Not Considered

Table 91. Road Infrastructure Operation Water Consumption Results, 2010 Base Case.

Road Operation	Annual Electricity Water, l/km	Annual Paint Water, l/km	Annual Deicing Water, l/km
Highway	0.184	0.097	870.96
Arterial	0.004	0.162	229.2
Collector	0.004	0.49	63.794

Table 92. Vehicle Infrastructure Operation Water Consumption Results, 2010 Base Case.

Vehicle Infrastructure	Daily Service Water, l/day (per vehicle)	Daily Bus Service Water, l/day (per vehicle)
Car Wash	1.618	3.503
Vehicle Service	10.759	100.132

B.2.2. Detailed Results for 2010 Washington State Scenario

Table 93. Automobile Fleet Usage Water Consumption Results, 2010 Base Case.

Auto-mobile Type	Fuel Usage Water, l/km	Fluid Cons-umption Water, l/km	Total Usage Water, l/km	Number of Vehicles	Total Usage Water, Aggregate, l/km	DVKT, km/day	Total Daily Travel Usage Water, Aggregate, l/day
Biodiese l	0.833	0.003	0.83	0	0	35.2	0
Corn Ethanol	1.353	0.003	1.356	119972	162,682.032	35.2	5,726,407.53
Gasoline	0.136	0.003	0.139	2158060	299,970.34	35.2	10,558,956
CNG	0.04	0.002	0.042	9266	389.172	35.2	13,698.8544
EV	3.035	0.0004	3.036	238	722.568	35.2	25,434.39
HEV	0.0945	0.002596	0.097	75784	7,351.048	35.2	258,756.89
PHEV	2.651	0.003	2.654	0	0	35.2	0
Total							16,583,253.6

Table 94. Automobile Fleet Usage Water Consumption Results, 2010 Base Case.

Bus Type	Fuel Usage Water, l/km	Fluid Cons-umption Water, l/km	Total Usage Water, l/km	Number of Vehicles	Total Usage Water, Aggregate, l/km	DVKT, km/day	Total Daily Travel Usage Water, Aggregate, l/day
Biodiesel	7.42	0.017	7.437	0	0	237.5	0
Corn Ethanol	9.238	0.017	9.255	0	0		0
CNG	0.393	0.017	0.41	454	186.14		44,208.25
EV	6.249	0.001	6.25	0	0		0
Diesel	0.929	0.017	0.946	161	152.306		36,172.675

Table 95. Electricity Generation Water Consumption Results, 2010 Base Case.

Electricity Source	Fuel Water, l/kWh	Plant Operation Water, l/kWh	Total Water, l (per month)
Coal	0.45	2.6	1,875,750,000
Oil	0.09	0.61	2,800,000
NGCC	0.087	1.02	1,264,194,000
Nuclear	0.132	3.2	2,728,908,000
Hydro	0	12.075	56,440,419,600
PV Solar	0	0.022	0
Wind	0	0.004	487,629.36
Wood Waste Biomass	0	1.8	686,239,416
Corn Ethanol	16.052	1.7	0
Biodiesel	5.507	1.7	0
Total	*Thermo*	6,557,891,416	
	Renewable	56,440,907,229	
	Total	62,998,798,645	
	Normalized	8.827	

Table 96. Vehicle Infrastructure Operation Water Consumption Results, 2010 Washington Case.

Vehicle Infrastructure	Daily Service Water, l/day (per vehicle)	Daily Bus Service Water, l/day (per vehicle)
Car Wash	1.618	3.503
Vehicle Service	14.039	131.225

B.2.3. Detailed Results for 2030 Georgia Scenario

Table 97. Automobile Fleet Usage Water Consumption Results, 2030 Georgia Case.

Auto-mobile Type	Fuel Usage Water, l/km	Fluid Cons-umption Water, l/km	Total Usage Water, l/km	Number of Vehicles	Total Usage Water, Aggregate, l/km	DVKT, km/day	Total Daily Travel Usage Water, Aggregate, l/day
Biodiesel	0.653	0.003	0.655	203165	133073.075		5,974,981.07
Corn Ethanol	1.036	0.003	1.034	447622	462841.148		20,781,567.6
Gasoline	0.107	0.003	0.11	1791464	197061.04	44.9	8,848,040.69
CNG	0.031	0.002	0.033	1978	65.274		2930.8026
EV	0.877	0.001	0.878	4862	4268.836		191,670.7364
HEV	0.074	0.003	0.077	55783	4295.291		192,858.57
PHEV	1.591	0.003	1.594	532643	849032.942		38,121,579.1
Total							74,113,628.5

Table 98. Bus Fleet Usage Water Consumption Results, 2030 Georgia Case.

Bus Type	Fuel Usage Water, l/km	Fluid Cons-umption Water, l/km	Total Usage Water, l/km	Number of Vehicles	Total Usage Water, Aggregate, l/km	DVKT, km/day	Total Daily Travel Usage Water, Aggregate, l/day
Biodiesel	4.553	0.017	4.536	0	0		0
Corn Ethanol	9.238	0.017	9.255	0	0		0
CNG	0.292	0.017	0.309	602	186.018	237.5	44,179.275
EV	1.053	0.0004	1.054	0	0		0
Diesel Hybrid	0.568	0.017	0.585	175	102.375		24,314.06

Table 99. Electricity Generation Water Consumption Results, 2030 Georgia Case.

Electricity Source	Fuel Water, l/kWh	Plant Operation Water, l/kWh	Total Water, l (per month)
Coal (Subcritical & Supercritical)	0.45	0.936	6,992,670,000
Oil	0.09	0.61	3,462,600
NGCC	0.087	1.02	1,738,946,900
Nuclear HTGR	0.132	2.2	8,028,930,000
Hydro	0	179.503	33,547,593,000
PV Solar	0	0.022	0
Wind	0	0.004	0
Wood Waste Biomass	0	1.8	468,434,608.4
Corn Ethanol	16.052	1.7	0
Biodiesel	5.507	1.7	0
Total	*Thermo*	17,369,871,177	
	Renewable	33,547,779,463	
	Total	50,917,650,640	
	Normalized	5.237	

Table 100. Total Road Infrastructure Operation Water Consumption Results, 2030 Georgia Case.

Road	Annual Maintenance Per Distance, l/km	Annual Operation Per Distance, l/km	Total Daily Maintenance Water, l/day	Total Daily Operation Water, l/day	Total Daily Water, l/day	Distance, km
Highway	0.011	871.195	0.151	12140.407	12,140.557	4700.8
Arterial	0.003	229.364	0.158	12140.407	10,686.853	17006.4
Collector	0.003	64.287	0.079	12140.407	1,562.124	8868.8
Total					24,388.298	

Table 101. Vehicle Infrastructure Operation Water Consumption Results, 2030 Georgia Case.

Vehicle Infrastructure	Daily Service Water, l/day (per vehicle)	Daily Bus Service Water, l/day (per vehicle)
Car Wash	1.618	3.503
Vehicle Service	8.364	77.845

B.2.4. Detailed Results for 2030 Washington Scenario

Table 102. Automobile Fleet Usage Water Consumption Results, 2030 Washington State Case.

Auto-mobile Type	Fuel Usage Water, l/km	Fluid Cons-umption Water, l/km	Total Usage Water, l/km	Number of Vehicles	Total Usage Water, Aggregate, l/km	DVKT, km/day	Total Daily Travel Usage Water, Aggregate, l/day
Biodiesel	0.653	0.003	0.655	203165	133,073.075	35.2	4,684,172.24
Corn Ethanol	1.036	0.003	1.034	447622	462,841.148		16,292,008.41
Gasoline	0.107	0.003	0.11	1791464	197,061.04		6,936,548.61
CNG	0.042	0.002	0.044	1978	87.032		3,063.53
EV	1.451	0.0004	1.452	4862	7,059.624		248,498.76
HEV	0.074	0.003	0.077	55783	4,295.291		151,194.24
PHEV	2.583	0.003	2.586	532643	1,377,414.8		48,485,000.9
Total							74,113,628.5

Table 103. Bus Fleet Usage Water Consumption Results, 2030 Washington State Case.

Bus Type	Fuel Usage Water, l/km	Fluid Cons-umption Water, l/km	Total Usage Water, l/km	Number of Vehicles	Total Usage Water, Aggregate, l/km	DVKT, km/day	Total Daily Travel Usage Water, Aggregate, l/day
Biodiesel	4.553	0.017	4.536	0	0	237.5	0
Corn Ethanol	9.238	0.017	9.255	0	0		0
CNG	0.3	0.007	0.31	602	186.018		44,179.275
EV	1.053	0.0004	1.054	0	0		0
Diesel Hybrid	0.568	0.017	0.585	175	102.375		24314.0625

Table 104. Electricity Generation Water Consumption Results, 2030 Washington State Case.

Electricity Source	Fuel Water, l/kWh	Plant Operation Water, l/kWh	Total Water, l (per month)
Coal (Subcritical & Supercritical)	0.45	0.936	854,762,977.4
Oil	0.09	0.61	2,229,146.372
NGCC	0.087	1.02	1,532,676,467
Nuclear HTGR	0.132	2.2	2,205,810,046
Hydro	0	179.503	67,260,829,219
PV Solar	0	0.022	0
Wind	0	0.004	581,107.908
Wood Waste Biomass	0	1.8	817,798,374
Ethanol	16.052	1.7	0
Biodiesel	5.507	1.7	0
Total	*Thermo*	5,413,227,011	
	Renewable	67,261,410,327	
	Total	72,672,459,310	
	Normalized	8.662	

B.2.5. Detailed Results for 2030 Hypothetical Scenario

Table 105. Automobile Fleet Usage Water Consumption Results (Per Kilometer Driven), 2030 Hypothetical Case.

Automobile Type	Fuel Usage Water, l/km	Fluid Consumption Water, l/km	Total Usage Water, l/km	Number of Vehicles	Total Usage Water, Aggregate, l/km
Biodiesel Hybrid	1.18	0.003	1.183	200000	236,600
Ethanol Mix	0.6969	0.003	0.6795	200000	135,894.8
Gasoline	0.11	0.003	0.113	200000	22,600
CNG	0.04	0.002	0.041	600000	24,600
EV	0.182	0.0004	0.183	500000	91,500
Gasoline HEV	0.069	0.003	0.072	100000	7,200
PHEV	0.428	0.003	0.431	200000	86,200

Table 106. Bus Fleet Usage Water Consumption Results, 2030 Hypothetical Case.

Bus Type	Fuel Usage Water, l/km	Fluid Consumption Water, l/km	Total Usage Water, l/km	Number of Vehicles	Total Usage Water, Aggregate, l/km
Biodiesel Hybrid	7.122	0.017	7.139	140	999.46
Ethanol Mix	5.865	0.017	5.849	0	0
CNG	0.39	0.017	0.407	420	170.94
EV	0.672	0.001	0.672	140	94.08
Diesel	0.929	0.017	0.946	0	0

Table 107. Yearly Electricity Generation Water Consumption Results, 2030 Hypothetical Case.

Electricity Source	Fuel Water, l/kWh	Plant Operation Water, l/kWh	Total Water, l (per year)
Coal IGCC	0.576	0.655	2.75E+12
NGCC	0.087	0.015	7.43E+10
Nuclear HTGR	0.132	2.2	2.14989E+12
PV Solar	0	0.022	89,578,827,520
Wind	0	0.004	1,456,000,000
Ethanol Mix	1.898	0	9.35E+10
Biodiesel Mix	2.303	0	1.04E+11
Total	*Thermo*	5.18E+12	
	Renewable	91034827520	
	Total	5.27E+15	
	Normalized	1.237	

Table 108. Vehicle Infrastructure Operation Water Consumption Results, 2030 Georgia Case.

Vehicle Infrastructure	Daily Service Water, l/day (per vehicle)	Daily Bus Service Water, l/day (per vehicle)
Car Wash	1.618	3.503
Vehicle Service	1.975	18.385

B.2.6. Detailed Results for 2010 Baseline Scenario With Fuel Mining Values Included

Table 109. Automobile Fleet Usage Water Consumption Results (Per Kilometer Driven), 2030 Hypothetical Case.

Auto-mobile Type	Fuel Usage Water, l/km	Fluid Cons-umption Water, l/km	Total Usage Water, l/km	Number of Vehicles	Total Usage Water, Aggregate, l/km	DVKT, km/day	Total Daily Travel Usage Water, Aggregate, l/day
Biodiesel	0.833	0.003	0.83	0	0	44.9	0
Corn Ethanol	1.353	0.003	1.356	119972	162,682.03		7,304,423.2
Gasoline	0.332	0.003	0.334	2158060	720,792.04		32,363,562.6
CNG	0.04	0.002	0.042	9266	389.172		17,473.82
EV	2.341	0.001	2.342	238	557.396		25,027.08
HEV	0.231	0.003	0.233	75784	17,657.67		792,829.47
PHEV	2.483	0.003	2.486	0	0		0
Total							40,503,316.2

Table 110. Bus Fleet Usage Water Consumption Results, 2030 Hypothetical Case.

Bus Type	Fuel Usage Water, l/km	Fluid Cons-umption Water, l/km	Total Usage Water, l/km	Number of Vehicles	Total Usage Water, Aggregate, l/km	DVKT, km/day	Total Daily Travel Usage Water, Aggregate, l/day
Biodiesel	7.42	0.017	7.437	0	0	237.5	0
Corn Ethanol	9.238	0.017	9.255	0	0		0
CNG	0.391	0.017	0.407	454	184.778		43,884.78
EV	4.660	0.001	4.661	0	0		0
Diesel	2.265	0.017	2.282	161	367.402		87,257.98
Total							131,142.75

Table 111. Yearly Electricity Generation Water Consumption Results, 2030 Hypothetical Case.

Electricity Source	Fuel Water, l/kWh	Plant Operation Water, l/kWh	Total Water, l (per year)
Coal	0.461	2.6	1.50E+10
Oil	0.416	0.61	8,208,000
NGCC	0.087	1.02	1,501,092,000
Nuclear	0.332	3.2	1.07E+10
Hydro	0	179.503	3.34E+10
PV Solar	0	0.022	0
Wind	0	0.004	0
Wood Waste	0	1.8	466,200,000
Corn Ethanol	16.052	1.7	0
Biodiesel	5.507	1.7	0
Total	*Thermo*	27,725,327,000	
	Renewable	3.34E+10	
	Total	6.11E+10	
	Normalized	6.81	

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